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FINAL REPORT

WATERWAYS SCIENCE AND TECHNOLOGY

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INSTITUTE FOR WATER RESOURCES
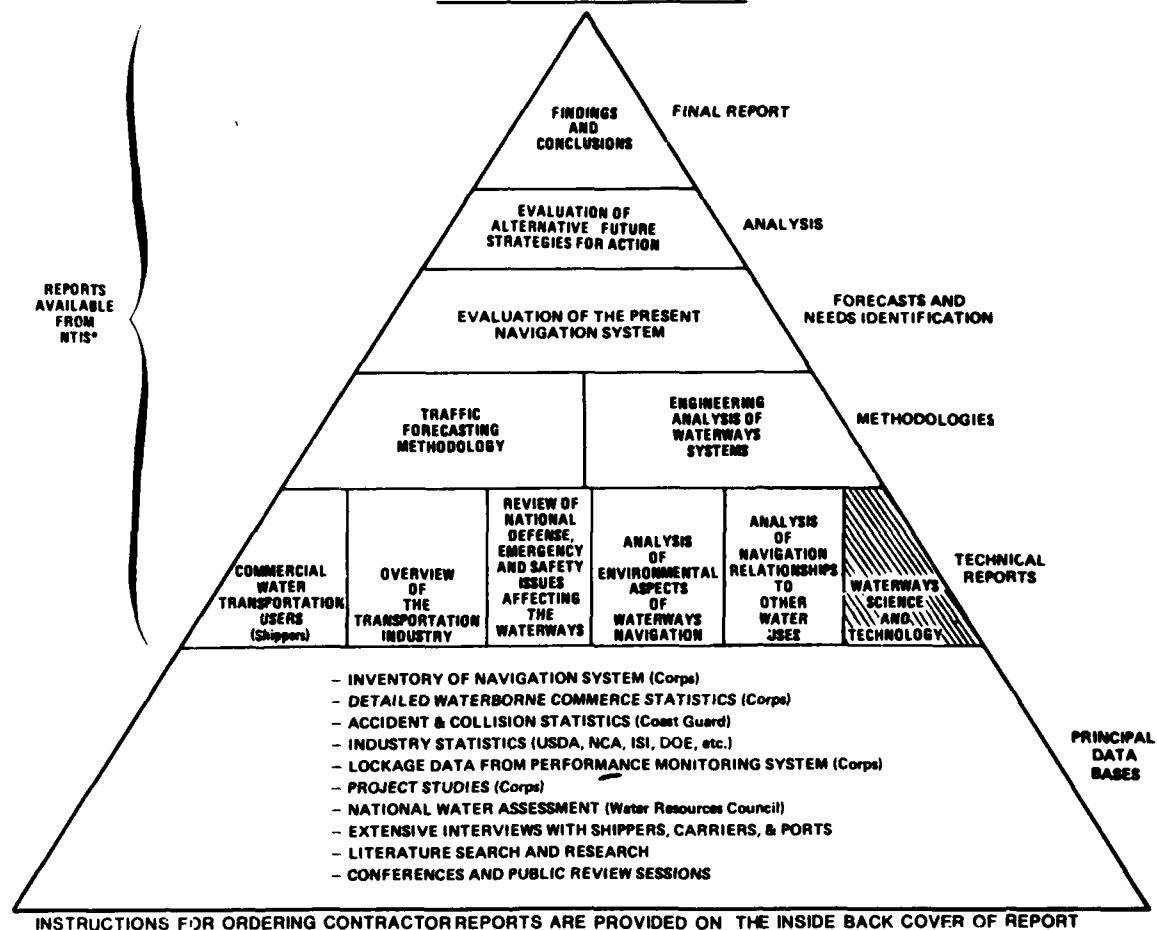WATER RESOURCES SUPPORT CENTER
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This report, Waterways Science and Technology, is structured according to the following six topics, which encompass major areas of waterways science and engineering: 1) Navigation Structures; 2) Methods of Increasing the Capacity of Existing Locks; 3) Channel Design Standards; 4) River Training Technology; 5) Dredging Technology; and 6) Technology for the Extension of the Navigation Season.

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NATIONAL WATERWAYS STUDY

WATERWAYS SCIENCE AND TECHNOLOGY

PREFACE

This report is one of eleven technical reports provided to the Corps of Engineers in support of the National Waterways Study by A. T. Kearney, Inc. and its subcontractors. This set of reports contains all significant findings and conclusions from the contractor effort over more than two years.

A. T. Kearney, Inc. (Management Consultants) was the prime contractor to the Institute for Water Resources of the United States Army Corps of Engineers for the National Waterways Study. Kearney was supported by two subcontractors: Data Resources, Inc. (economics and forecasting) and Louis Berger & Associates (waterway and environmental engineering).

The purpose of the contractor effort has been to professionally and evenhandedly analyze potential alternative strategies for the management of the nation's waterways through the year 2000. The purpose of the National Waterways Study is to provide the basis for policy recommendations by the Secretary of the Army and for the formulation of national waterways policy by Congress.

This report forms part of the base of technical research conducted for this study. This report focuses on six major areas of waterways science and engineering, including a discussion of navigation structures and development and management of the river system. The results of this analysis were reviewed at public meetings held throughout the country. Comments and suggestions from the public were incorporated.

National Waterways Study

FINAL REPORT

WATERWAYS SCIENCE AND TECHNOLOGY

UNITED STATES CORPS OF ENGINEERS

WATERWAYS SCIENCE AND TECHNOLOGY

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EXECUTIVE SUMMARY

This report is structured according to the following six topics, which encompass major areas of waterways science and engineering:

1. Navigation Structures.

2. Methods of Increasing the Capacity of Existing Locks.

3. Channel Design Standards.

4. River Training Technology.

5. Dredging Technology.

6. Technology for the Extension of the Navigation Season.

The complexity of lock design, and the type of construction involved to a large extent for lifts of under five feet, locks with earth embankment walls may suffice. For lifts over 50 feet, the only choice is concrete construction with a hydraulically well designed filling and emptying system.

For concrete locks, foundation conditions at a specific site, where the lift is over 10 feet, may determine whether the lock will be designed with: gravity walls supported on soil; gravity walls supported on friction piles; gravity walls supported on end bearing piles; gravity walls on rock; drydock type structures supported on soil; or dry dock type structures supported on piles.

Simplified less costly 'ypes of locks can be designed, but in all cases filling and emptying times will be increased, safety will be lower, and the capac'ty will be lower than the capacity of a conventional iesign concrete lock that can be filled or emptied more rap'. y.

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In the future, very low lift locks probably will be of the embankment type in sizes up to 600'x110'. For sizes larger than this, for heavier tows, and where traffic density is greater, concrete construction will probably be required.

Hydraulic model studies, and verification of the model studies with full scale prototype tests, examining channel levels, river currents and channel depths, are an absolute necessity if costly mistakes in lock siting are to be avoided.

At locations where it becomes necessary to build two locks, based on the results of model studies, two layouts have been developed which when adopted at future sites should provide safer and more efficient movement of traffic through the locks. The first layout uses adjacent locks and the second uses separate locks. When locks are to be placed adjacent to each other, it is preferable to separate them with relatively long guide walls providing enough space to permit simultaneous movement of vessels into and out of both locks. Alternately, the two locks should be separated by 1.5 to 3.0 locks widths with a section of spillway between them so that all flow upstream from the locks is not blocked.

Particular attention has to be given to the layout of a lock that is being placed in a dam where hydropower is a main feature. The lock must be located so that flow to the powerhouse as well as to a spillway will not create adverse currents in the lock approaches.

In the early 1960s, attempts were started to fix certain standard lock sizes to prevent a continued proliferation of sizes. The sizes recommended for commercial locks are 84'x400', 84'x600', 84'x720', 84'x1200', 110'x600', 110'x800' and 110'x1200'. It is anticipated that further needs for lock sizes will continue in the 84 to 110 foot widths and 400 to 1200 foot lengths.

Research during the past 20 years has fairly well determined the characteristics and defined limitations of the four general types of filling and emptying systems.

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On secondary waterways with lifts in the very low to low
lift ranges, end systems and side port systems will con-
tinue to be used. Designs for side port filling systems
have been standardized so that design of these systems
under normal conditions in three sizes can be developed
without resorting to model studies. For intermediate and
high lift locks, it will probably be necessary to use con-
crete locks with bottom longitudinal systems. However,
designs for intermediate and high lift locks must be
selected after economic comparison with side port and
multiport systems, particularly for lock lengths of 600
feet or less. Thus far, there have not been enough locks
built using bottom longitudinal systems to allow their
design without model studies. Thus, high lift locks to be
constructed in the foreseeable future will require hy-
draulic model testing of the filling system in order to
insure adequate design.

The reverse tainter filling and emptying valve has
been widely adopted in the United States for all concrete
locks in the low to high lift classifications with side
port, bottom lateral or bottom longitudinal systems. In
future lock construction, reverse tainter valves will be
used more than any other type.

For the foreseeable future, lock gates in the United
States will probably be miter, vertical sector, submerg-
ible, tainter or overhead vertical lift types. Most
future locks will have miter gates. For very high lift
locks, submergible upstream tainter gates and overhead
vertical lift gates or miter gates will probably be used.
For very low lift locks, either miter gates or sector
gates may be used (sector gates where head reversals are
possible.

Poor approach conditions currently exist at some locks
which could have been mitigated if modern, improved design
techniques had been available at the time of construction.
For many of these locks, improvements may be possible by
modifying the existing approaches.

To date, no research has been performed in the United
States to evaluate the effect of reduced clearances on
lock service time and navigation safety. Thus, no precise

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assessment can be made of the effect of clearance on lock capacity based on American research with tow sizes and lock sizes in use in the United States.

Studies have shown that the use of water saving basins (thrift basins) should be considered in areas where adequate water may not be available to allow regular cycling of a lock.

In general, whenever lifts have exceeded about 65 feet, Europeans have found shiplifts more competitive than high lift locks for vessels with a cargo capacity of 1350-1500 tons. According to studies made in the Union of Soviet Socialist Republics, the installation of shiplifts becomes feasible for vessels designed for a cargo carrying capacity of 5000 tons, beginning with lifts of 165 to 200 feet. This limit is evidently in the neighborhood of 130 feet with 2000-3000 ton vessels.

Currently, no shiplifts have been constructed with a length exceeding 330 feet, so that barge tows must break before using them. Due to the very small size of the shiplifts, which would only be capable of accommodating one or two United States barges, it is very unlikely that the use of shiplifts instead of locks could be justified in the United States.

During recent years, heavy construction has benefited enormously from the technological progress and widespread use of prestressing techniques within the construction industry. Economics may, in the future, be achieved by precasting various elements of a lock structure and/or by precasting entire segments of locks and assembling them by using post-tensioning and prestressing methods.

As a result of technological improvements in the design of locks and dams over the past several decades, navigation safety has improved, service times have decreased, maintenance requirements have decreased and operation has improved. Savings in these areas resulting from the improvements are believed to have offset the increased construction costs which in many cases have resulted.

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It is likely that continued investigation to improve the safety, and other aspects, of lock facilities will result in additional improvements which will add to the cost of the lock facility. However, as additional work is performed to generalize design for gates, valves, and filling systems, the engineering cost to develop or adapt these designs on a site specific basis will be reduced.

The cost of locks and dams may also be reduced as new heavy construction techniques discussed are applied in the construction of lock facilities or as additional techniques are developed. The use of some new techniques may actually increase costs, as it may be possible to develop new designs which were considered infeasible, using conventional construction techniques (the offsite prefabrication construction of lock segments to be floated into place, for example).

Methods which have been proposed to increase the capacity of locks logically fall into two categories of technological feasibility, those measures which have been and are currently used, and those which may find application after additional research is conducted.

Measures which are currently used to increase the capacity of locks include:

- improvements in lock operating equipment.

- improving lock approaches.

- provision of mooring cells.

- installation of wind deflectors.

- installation of tow haulage equipment.

- installation of floating mooring bitts.

- greater use of the auxiliary chamber.

- invoking an N-up/N-down policy.

- use of switchboards.

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- guide wall extension.

- invoking a Ready-to-Serve policy.

Measures which may find application in increasing the capacity of locks include:

1. centralization and automation of controls.

2. provision of separate facilities for recreational craft.

3. installation of impact barriers.

4. installation of replaceable fenders, energy absorbers and/or rolling fenders.

5. provision of waiting areas near lock gates.

6. establishment of more responsive and flexible scheduling procedures.

7. water traffic regulation.

8. industry improvements such as increased tow powering, use of bow thrusters, use of universally adaptable coupler for joining barges and others.

To date, all quantitative results of investigations to increase capacity by non-structural and minor structural means have been obtained for specific locks so that in order to identify the benefits (in terms of increased lock capacity) possible at other locks, site specific information must be obtained. The development of generalized relationships which could be used to evaluate the relative benefits and costs of these measures would be highly desirable and facilitate their investigation at other sites.

Channel design standards are based on a given set of conditions, tow size, and horsepower; private towing companies may find it economical to operate larger tows in less favorable conditions, trading off the increased difficulty of navigation for the economies of scale of larger tows.

The selection of design depth is largely an economic decision once the physical requirements for the passage of vessels have been met. It is unlikely, however, that reductions in transit time or fuel consumption could justify the cost of constructing and maintaining a channel significantly deeper than the minimum requirement. In practice, tow operators load their barges to whatever draft will allow them the clearance which they feel is acceptable. This draft is often 8 or 8.5 feet in a 9 foot channel, less if the bottom is hard or the cargo is hazardous. Thus, a design standard of one foot of clearance in inland waterways after draft, sinkage, trim, and waves have been accounted for is effectively maintained in the United States.

A by-product of the new technologies which have been developed to increase the safety of tow operations is the ability of large tows to operate in smaller channels, or with less restriction in the same channels, than before. Advances in towboat technology effectively allow channel design standards to be eased.

Many waterways in the United States are located on natural rivers which carry a high sediment load. Such rivers are highly dynamic with significant seasonal and annual changes in channel dimensions and alignment. River training and dredging are utilized to maintain these channels for navigation. River training may be divided into three entities--dikes, revetments, and cutoffs.

Considerable research has been undertaken in the fields of sediment movement and river mechanics. There is, however, insufficient knowledge in such areas as sediment discharge and river morphology which would allow accurate prediction of river response from river training projects. Consequently, most river training is conducted on a subjective and individual basis by experienced engineers with only general guidelines to aid their decisions. Larger, more complex projects are studied on movable-bed models to evaluate proposed river training structures and optimize performance.

A regional description of river training shows significant differences in approaches between districts. Dike

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construction generally utilizes rock dikes. In some
cases, notched dikes are used for creating and/or main-
taining side channel openings to improve fish habitat and
for boat passages.

Bank stabilization and revetment projects generally
use rock riprap or, on the Lower Mississippi River, artic-
ulated concrete mattresses are used. The methodology in
bank stabilization has not changed significantly in the
past 30 years. The concrete mattress, in a sense, was a
technological revolution. The passage of the Stream Bank
Erosion Control Act, however, underlined the concern that
exists regarding bank erosion. Under this Act research is
being conducted to further define the causes of bank ero-
sion and to develop possible remedies. Emphasis is being
placed on cost effective techniques especially the use of
waste or low cost materials.

Bank erosion has become a subject of particular inter-
est because of allegations relating bank erosion to navig-
ation. While there are local areas of concern, recent
evidence indicates that most bank erosion occurs as a re-
sult of seasonal variations in stream flow.

The use of cutoffs was primarily concentrated on the
Lower Mississippi River during the 1930s and 1940s. No
additional cutoffs have been proposed on the Mississippi
River although other non-free flowing rivers have since
utilized cutoffs as a river training technique. While
cutoffs have shortened the river and provide a more favor-
able alignment for navigation, there is some evidence that
channel depths have been reduced in certain reaches and
cutoffs often induced bank instability. The effect of
cutoffs is a long-term phenomenon and, based on the
Mississippi River experience, it is not yet clear as to
the final effect that cutoffs produce in alluvial
channels.

In consideration of regional variations the state-of-
the-art in river training, nonetheless, can be generaliz-
ed. The design of dikes is based on the local currents in
a reach, the movement of sediment, and the effects of the
resulting currents on navigation. Presently, the design
of training structures is based on the experience of the

engineers or movable bed models since only limited basic
design criteria exist.

Historiclly, the general dredging practice employed in
the maintenance of the nation's waterways was that which
would accomplish the taks at the lowest overall cost.
Since the mid 1960s, though, other considerations have
also come to play a significant role in the evaluation of
a dredging project.

In addition, a continuing emphasis is being placed on
the benefits which could be derived from the many applic-
able productive use concepts.

Five hypothetical settings for dredging and disposal
operatons have been formulated depending on specific
dredging or disposal requirements. Based on these re-
quirements and their severity, the options for specific
dredge plant types and discharge loading, transport, and
unloading methods become more limited. In turn, these
factors will detemrine the costs of operation.

More rigid requirements and considerations in some of
the waterways have greatly increased dredging costs.
Improvements in dredge technology and in efficiency of
dredge operation are the two main elements which tend to
counteract increased dredging costs resulting from these
requirements.

Although the existing United States dredging fleet may
be condisdered capable of adequately permforming the for-
seeable dredging workload, modernization is unquestionably
desirable in order to increase the overall effectiveness
in accomplishing work under varying conditions. These are
influenced significantly by present and anticipated dis-
posal requirements. Also, in the case of certain diffi-
cult dredging problems associated with waterway mainten-
ance, there is an apparent need for developing new dredg-
ing plant concepts.

Applied research and development of dredging systems
has been applied and continues to be undertaken by the

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Corps of Engineers, dredging equipment manufacturers, and a few dredging contractors. The innovations associated with these developmental efforts generally are intended to improve productivity, effectiveness, and versatility of the dredges.

Recent developments in the technology for extension of the navigation season can reduce the cost of continuing waterborne transportation into the winter, and can increase the capacity, reliability, and level of safety of winter waterway operations.

At locks, the use of air screens and diversion channels rather than personnel with pike poles to keep floating ice out of the chamber and especially out of gate recesses reduces the operating cost of the lock and increases the lock capacity as the time spent clearing the chamber of ice is reduced. The use of a specialized ice saw or heating elements to remove the ice collar around lock walls, instead of scraping it off with a backhoe, saves time and money and reduces damage to the lock, improving reliability. Polymer coating on lock walls and gates further reduces the time and expense associated with ice removal. Heating of lock machinery and the use of low temperature lubricants improves reliability, as the machinery is protected from the rigors of winter operation.

Ice booms promote the formation of a stable ice cover through which vessels can pass without help from icebreakers, reducing cost. Safety and reliability are increased as ice jams are prevented from forming and the risks of flooding or formation of an impassible wall of ice are reduced. Improvements in the effectiveness of icebreakers, such as hull coating and air screen systems, which reduce drag, and the application of ACV technology. reduce the cost of icebreaking and enable the icebreaking fleet to increase the level of the availability of the channel. The development of cargo vessels which do not require icebreaker escorts reduces icebreaker requirements. Bubbler systems aid warm effluent can prevent ice from forming, reducing the cost of vessel operations. Electronic aids to navigation which replace buoys reduce the cost of maintenance of the buoys and provide increased safety and reliability for vessel operations through their accuracy and ease of use in all weather conditions. Ice

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forecasting, surveillance, and information systems provide
increased safety and reliability to vessels and reduce
cost, as ships can avoid any hazards on impassable
reaches, and can identify the route presenting the thin-
nest ice.

Better understanding of structural design for ice
loads allows structures to be designed with appropriate
safety risks. Cargo handling technology, which expedites
vessel loading and unloading in ice conditions, reduces
port time for vessels with associated cost savings.

These technological improvements in safety, reliabil-
ity and capacity and reductions in cost make season exten-
sion proposals more attractive. Programs calling for add-
itional extensions, both geographical and seasonal, which
were only marginally feasible in the past, may now be ac-
ceptable, if new technologies are employed.

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I - INTRODUCTION

This report is part of the overall National Waterways Study which is composed of 14 separate yet interactive elements having the collective objective to "Identify and Analyze Alternative Strategies for Providing a Navigation System to Serve the Nation's Current and Projected Transportation Needs."

In the National Waterways Study Overall Objective, this report provides an assessment of the most likely trends in current and ongoing research in the field of waterway science and engineering which may affect the future water transportation system.

The report addresses the waterway science and technology under six major topics. These comprise the six major sections:

1. Navigation Structures.

2. Methods of Increasing the Capacity of Existing Locks.

3. Channel Design Standards.

4. Dredging Technology.

5. River Training Technology.

6. Technology for the Extension of the Navigation Season.

Within each section, the current state-of-the-art is reviewed, recent and ongoing research is summarized, technological trends are assessed, alternative technologies discussed and directions for further research suggested.

In the initial section, "Navigation Structures," a general assessment of technological trends in the design of navigation locks and dams and the layout and configuration of navigation locks are provided.

In section IV, entitled "Methods of Increasing Capacity of Existing Locks," non-structural and low cost measures which may be effective in increasing the capacity of existing locks are assessed.

In Section V, entitled "Channel Design Standards," an attempt is made to define the minimum channel dimensions required to accommodate vessels/tows of various sizes and operational speeds.

Section VI, entitled "River Training Technology," presents an assessment of river training methods and a review of the effects of training on river hydraulics, and morphology and, consequently, on channel maintenance requirements.

Section VII, entitled "Dredging Technology," presents a general assessment of dredging methods and techniques and the effects of changing dredging and disposal requirements on dredging practices.

In Section VIII, "Technology for the Extension of the Navigation Season," is assessed.

In Section IX, "Directions for Future Research," recommendations are made for directions in which future research should be focused. Suggestions have been ranked according to their priority for short, intermediate, or long-term implementation

The material presented in this report is directed toward individuals involved in planning for waterway development and should not be considered as a substitute for design level efforts.

The design standards quoted in this report are the opinions of their authors, and do not necessarily constitute the policy of the Corps of Engineers. The policies of the Corps, as represented by the Corps of Engineers manuals or technical letters, are specifically identified in the text as such.

II - INFORMATION SOURCES

Information sources for this report were primarily limited by the scope of the study to available published information and interviews with Corps of Engineer experts.

The published sources of information used to prepare this report were reports, studies, investigations and evaluations supplied by the Corps of Engineers and literature obtained via a literature search. Information was provided by the staff of the following Corps offices:

1. Waterways Experiment Station.

2. Institute for Water Resources.

3. Board of Engineers for Rivers and Harbors.

4. Dredging Divisions.

5. Cold Regions Research and Engineering Laboratory.

Reports of private companies or individuals were obtained from a variety of sources including the National Technical Information Service, science and engineering journals and publications, and United States and European research centers.

Information pertaining to ongoing research, current trends and directions for future research was obatained primarily via interviews. Initially, the aforementioned Corps offices were visted and the various topics discussed with appropriate personnel. Where necesssary, follow-up visits were made to Corps District Offices. Subsequently, workshops were conducted in July, 1980 at the Waterways Experiment Station in Vicksburg, Mississippi and the North Central Division of the Corps of Engineers in Chicago, Illinois. The workshops were attended by the leading experts from the government, universities and private industry in each area investigated. The workshops provided an additional review of technology and an assessment and ranking of future research needs.

III - NAVIGATION STRUCTURES

NAVIGATION LOCKS AND DAMS

(a) Navigation Dams

A navigation dam is a structure built across a river
to create a pool, solely for navigation, that will provide
adequate depth for vessel traffic. A multipurpose dam may
also provide depths for navigation, but as the name im-
plies, other purposes such as hydropower and flood control
storage may be important and in some instances may be the
paramount purpose of the project. A non-navigable dam
forms a barrier to free movement of traffic, and all ves-
sels plying the waterway have to move from one side of the
dam to the other side by means of a lock. Non-navigible
dams may be further classified according to whether they
have a fixed or gated crest section. A gated section per-
mits better regulation of the upstream pool level. A non-
navigable dam with a gated section has control gates
arranged so that as river flow increases, the gates can be
opened to pass the increased flow and thereby reduce the
rise in stage upstream from the dam that would occur if
the structure had no control gates, i.e., if the dam had a
fixed crest. On a non-navigable dam with no movable or
control section, the fixed crest is usually fixed at or
slightly above the desired upper pool level during minimum
flow conditions and any increase in river flow will cause
an increase in the upper pool elevation as well as in the
lower pool. This type of dam would normally be used where
increases in flow up to bankfull stage are of short
duration and resulting flood damages are low.

A navigable dam generally has a movable section that
can be lowered to the approximate level of the river bed
during periods when river flow is great enough to provide
navigable depth. (Note: navigable dams, such as some on
the Ohio River, can also be designed with fixed crests
that can be navigated over during flood periods when the
lock is out of operation.) This type of dam may sometimes
be used to advantage on rivers where navigable depths
occur naturally for significant periods each year and
where there is a great range of stage from low flow to
medium and high flow. During the periods when flow is
great enough to provide navigable depths, the navigable
portion of the dam is lowered (collapsed on the dam sill)

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and vessels can move upstream or downstream across the dam without using the lock. This results in a great savings of time and cost where a canalized waterway requires a number of dams and locks. Figure III-A shows a sketch of the Chanoine wicket type dam. This type dam is limited to a wicket height of approximately 20 feet.

In considering the conversion of a natural stream into a canalized waterway, or the improvement of an existing canalized waterway, the slope of the stream, the topography of the flood plain, the development of the flood plain, the duration of critically low flow periods, the sediment characteristics of the stream, and the required minimum depth govern the general location and the number of dams needed. In order to minimize the number of dams and locks, the pools upstream from each dam should be made as long as possible without excessive inundation of valuable land and expensive developments. On the other hand, fewer dams and longer pools mean higher lifts, which reduce the percent of time that a navigable pass section can be used. Navigation dams must be designed to pass high flows and floods with minor swell head and without increasing the natural flood stages. Construction costs, land use and relocation costs, maintenance and operation costs and environmental effects must be considered and compared with anticipated benefits. On streams that do not have steep slopes and have sustained periods of flow that provide navigable depths, navigable dams may offer advantages over non-navigable structures. However, as will be discussed later, this type of structure has some serious limitations and has become almost obsolete in the United States.

On streams with steep slopes that experience long periods of non-navigable flow but have frequent short periods of high flow, non-navigable dams with movable crests (control gates) are required. In some instances, both types of dams may be utilized to advantage on the same waterway, and in some situations either type can be used.

In the initial development of canalized waterways in the United States the selection of the type of lock and the type of dam was influenced by the physical characteristics of the stream; the type and size of vessels to

Figure III-A

Chanoine wicket section of an Ohio River Dam

ELEMENTS OF LOCKS AND DAMS

High Water El. 3392
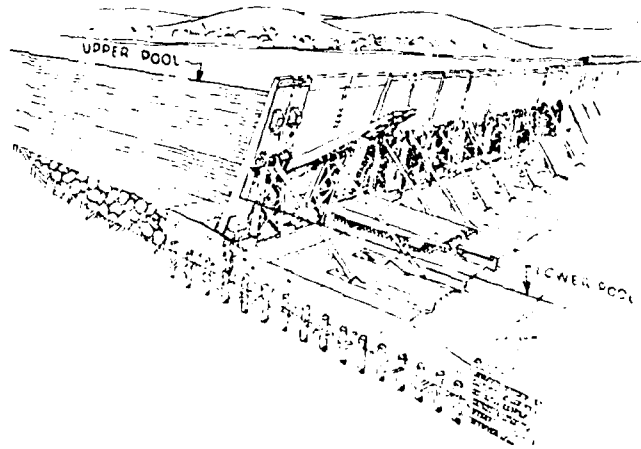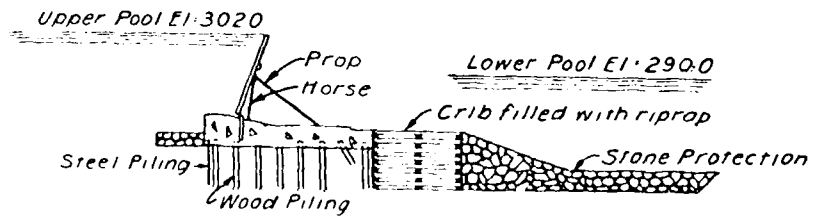
be served; and by limitations imposed by structural, hydraulic and foundation problems. On sand and gravel bed streams, engineers resist attempts to build structures with lifts much greater than 10 to 15 feet. (This was probably due to the great difficulty associated with constructing a stable gravity wall on pile foundations without experiencing serious deflections and settlement problems.) This had more influence on early navigation projects than any other single factor. Because of the low lifts, a greater number of dams and locks were required on a specific stream than would have been necessary if lifts could have been used. The low lift limitation was not the sole factor in selection of the type of locks and dam for a specific site on a specific waterway, but it was the principal one. The lift limitation had a significant influence on the selection of the navigable type dam for use in the early canalization of the Ohio River and several other streams. Lift also was a governing factor in the filling system designs of that era.

The use of navigable dams, in turn, influenced certain design features of the lock such as the height of the lock walls and gates. Where there was a great range in stage from low water to high water, and a navigable type of dam was used, it was not necessary to provide walls more than four or five feet higher than the maximum stage at which traffic ceased to use the lock. The walls, gates and operating equipment were designed to withstand submergence and high lock walls and greater costs were avoided.

Many changes and technological advances have occurred since the early development of locks and dams, and the maximum lift at specific site no longer is a limiting factor, provided a suitable foundation is available. However, the maximum lift at a site does influence many features of the design of a lock and may determine whether or not a navigable or non-navigable dam can be used.

The Ohio River navigation system provides a good example of the development of navigation facilities and of the reasons for the selection of different types of locks and dams. At the same time, the first Ohio River canalization projects were planned, around 1875 there were very few locks and lifts much greater than 10 or 15 feet; hydraulic design of locks was in the very beginning stage;

structural and foundation design of dams on a sand and
gravel stream bed to prevent erosion was not very well
developed; and most traffic consisted of downbound coal
movement during the high water season. This last factor
led to adoption of the first 600'x110' size locks, as
shippers did not want locks that could not transit a tow-
boat and fleet of ten coal barges in a single lockage.
The plans that were evolved between 1878 and 1910 met the
requirements of that era quite successfully. Since the
natural Ohio River flows were greater than needed to pro-
vide the desired channel depths for substantial portions
of the year (greater than 50%) considerable use was made
of navigable dams.

By 1929 the Ohio River was completely canalized with
locks and dams at 50 locations, of which 48 were navigable
type dams with Chanoine wickets and the other two were
non-navigable dams. Figure III-B shows a picture of one
of the old Ohio River navigable dams. Between 1929 and
1937, six of the original navigable dams were replaced
with two higher lift non-navigable dams. By the close of
World War II, conditions had changed drastically. Tow
operators were using larger tows; tonnage had increased
far beyond the expectations of 1929 and tonnage was moving
both upstream and downstream; technological advances had
been made in all phases of lock and dam design; and oper-
ating personnel costs were becoming more significant in
planning navigation improvements. When technological ad-
vances made possible the use of higher lifts for naviga-
tion dams and locks on the Ohio River, it became evident
that the necessity for tows to use the locks at each non-
navigable dam 100% of the time would be more than offset
by benefits from longer and deeper pools, larger locks,
reduced operating costs and generally more reliable navi-
gation conditions. These factors led to redevelopment of
the waterway with two locks and a non-navigable dam at
each of 14 new locations. There are presently locks and
dams at 20 locations, with navigable dams at only two of
the 20 sites (i.e., Locks and Dams 52 and 53). Some fixed
crest dams on the Ohio River are also designed to be navi-
gated over during flood periods when the locks are out of
operation.

Thus, on the Ohio River, either type dam can be used
but the change from navigable to non-navigable dams re-
sulted from changes in traffic; improvements in the

Figure III-B
A Dam of the Standard Ohio River Type
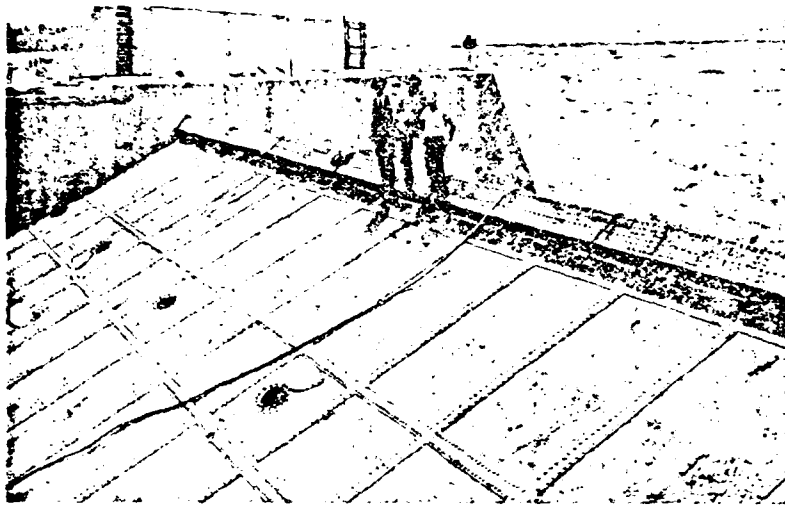
Dam No. 41, Ohio River
The crest of a beartrap
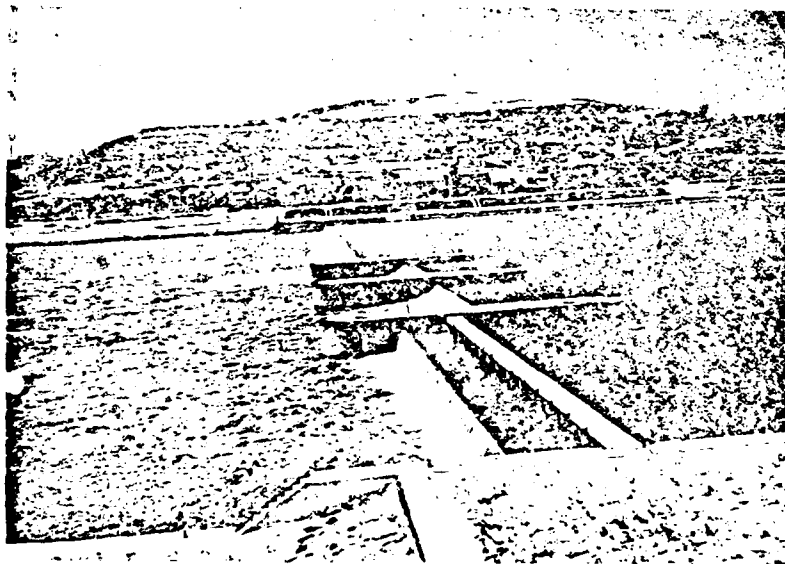
Lock and Dam No. 11, Ohio River
Figure III-B
A Dam of the Standard Ohio River Type

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state-of-the-art of design and construction of locks and dams; and the desire to reduce the number of lockages.

The experience on the Ohio River is cited to show and explain the factors that influence the selection of the type of navigation dam for a specific waterway.

Advances in technology have eliminated the structural and hydraulic limitations on use of higher lift locks and dams and as a result there has been only one navigation dam built with a navigable pass since 1937. Under today's conditions about the most likely location where a navigable dam would be feasible would be on a tributary of a fairly large stream where the large stream experiences long periods of high stages that create very flat backwater slopes for an appreciable distance up the tributary. There does not appear to be very much need or opportunity to consider navigable type dams in improving existing waterways or building new ones in the United States.

Other types of navigable dams have been proposed or are in use in other countries. An example is the "visor" dam in use in the Netherlands. Figure III-C shows an aerial view of the visor dam at Hagestein, Netherlands, constructed in 1962. This navigable visor dam and others, constructed more recently, on the Lower Rhine River in the Netherlands, are operated by lift cables and rest on a semi-circular sill which also acts as a weir to regulate flow. Visor dams in the Netherlands have operated satisfactorily and exhibit certain advantages. Chief among the advantages are: the 48m (157.5 ft.) navigable span; semi-circular shaped structure placed normal to the direction of flow with low bending moments; improved distribution of flows downstream, with single gate open, as a result of arc-shaped weir; relatively low weight (7m high gate, 48m span, 200 tons). Navigable visor dams in the Netherlands are also provided with cylinder valves for more accurate regulation of flow and conventional locks for periods when the dam cannot be navigated.

While other types of navigable dams would be investigated prior to the selection of a final design at a given

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Figure III-C

Visor Dam
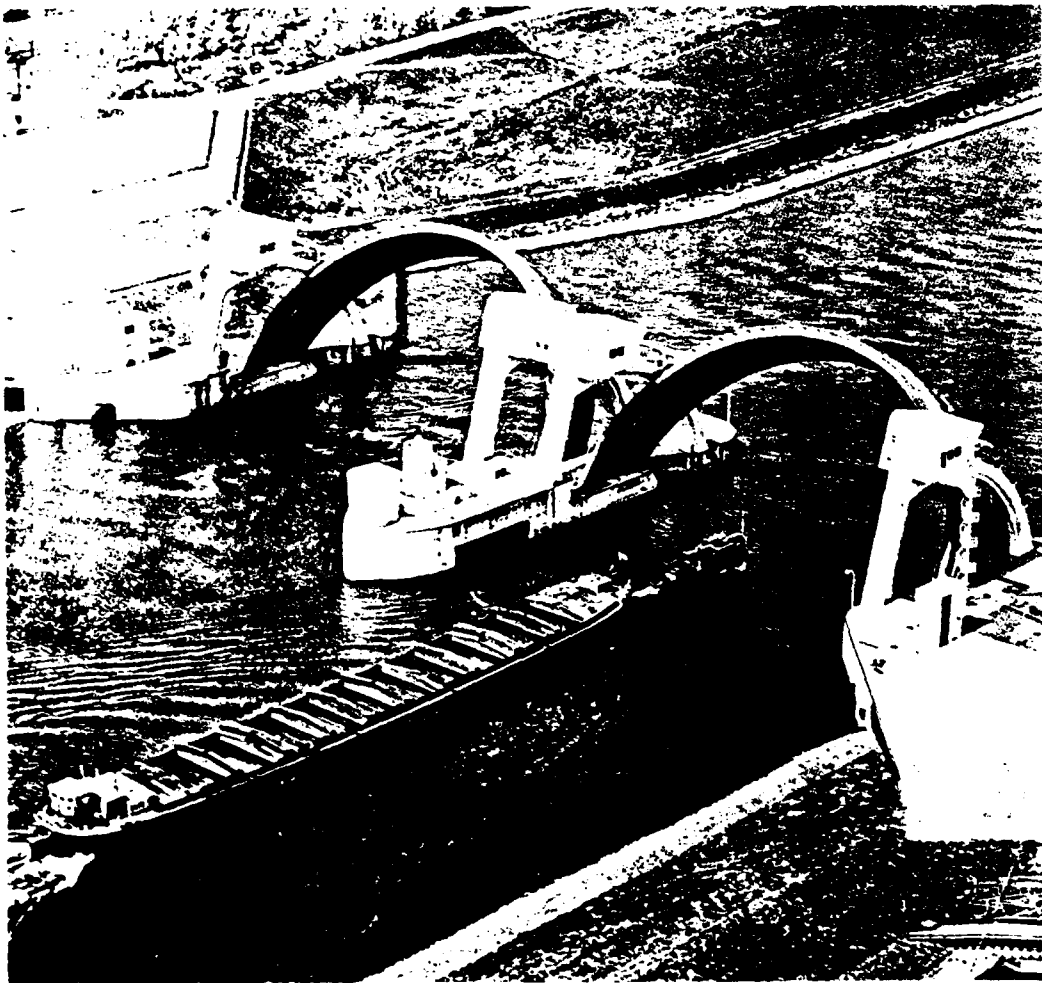
site, existing designs for different types of dams show no inherent advantages.

(b)   Navigation Locks

Navigation locks can be classified generally into three separate categories:

     1.   Inland Locks - shallow draft and the most important in the United States.

     2.   Maritime Locks - deep drift and potentially significant, but only the two old maritime locks for commercial vessels are in use in the United States.

     3.   Recreation Locks - inland and maritime locks for recreational craft, potentially significant.

Whether a lock is considered a maritime or inland lock depends on its location and the type of traffic that will use it. A lock in a tidal estuary, at a coastal harbor entrance or where an inland canal enters a coastal inlet and serves seagoing vessels is considered a maritime lock. Such a lock must have certain design features that make it distinctly different from an inland lock, even though it may also serve some inland type vessels. Locks situated on inland canals, canalized rivers and connecting channels between locks are considered as inland locks and, with the exception of the Soo Locks and the St. Lawrence Seaway Locks, are designed for shallow draft vessels, i.e., drafts of not more than 9 to 12 feet.

Designs for locks in each of the three categories discussed in the foregoing paragraphs are influenced by:

     1.   the general importance of the waterway.

     2.   the type, size, and number of vessels to be served at a specific site (a towboat and flotilla of barges is considered one type of vessel).

     3.   required capacity at a specific location.

     4.   the lift at the specific location.

     5.   foundation conditions at the site.

6. construction and maintenence costs at the
site.

7. sediment conditions.

8. river flow characteristics.

The first three items listed above are interrelated as
the importance of the waterway has a direct bearing on the
required capacity and on the type, size and number of ves-
sels to be served at a specific location.

At any specific site, the required capacity, the size
of vessels to be served, and the lift will govern the size
of the lock, the design of the filling system and the gen-
eral layout of the lock. The foundation conditions and
the lift will govern the type of construction to be used
and hence construction costs. Type of construction means
whether the lock is all concrete, sheet pile walls with
concrete bays or earth embankment walls with concrete gate
bays.

The importance of a waterway is a classification that
is intended to indicate whether the waterway is a primary
traffic artery; a more or less secondary route; or possi-
bly a minor tributary route serving a small geographic
area whose potential is limited. Examples are: a) pri-
mary artery - the Mississippi and Ohio Rivers from New
Orleans, Louisiana, to Pittsburgh, Pennsylvania; b) sec-
ondary route - the Morgan City Route, from the Mississippi
River at Baton Rouge to Morgan City, Louisiana, on the
Gulf Intracoastal Waterway; (c) tributary route - Green
River in Kentucky from the Ohio River to Rochester, Ken-
tucky. It is difficult to establish firm rules with
regard to rigidly classifying every waterway and there is
perhaps no need to do so. However, it must be recognized
that locks on the Green River in Kentucky should not be
designed to the same standards of size, performance and
reliability as the locks on the Ohio and Upper Mississippi
Rivers. It is obvious that locks built on such important
waterways must be larger, operate faster, and be capable
of withstanding use by larger numbers of heavier tows than
the locks on secondary or tributary waterways where tows
are limited to much smaller sizes by channel dimensions
and by lack of commerce.

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The required lock capacity at a specific location on a waterway can be obtained in different ways. For instance, if the majority of the tows are relatively small, but are very numerous, one large lock might not provide the capacity that two locks half as big might provide. Also, utilizing a faster, more expensive filling system may provide more than the required capacity under existing conditions, but, because of unforeseen events, might extend the time period before an additional lock is needed to the point where the added filling system cost becomes a wise investment.

Locks may be classified by lift as follows:

- very low lifts   lifts under 5 feet.

- low lifts   lifts from 5 to 30 feet.

- intermediate lifts   lifts from 30 to 50 feet.

- high lifts   lifts over 50 feet.

The above classification reflects, to a large extent, the complexity of design and the type of construction involed. As lifts increase, design of foundation, structural elements and hydraulic features become more critical. For lifts of under five feet; locks with earth embankment walls may suffice. But when lifts increase other types of construction (i.e., concrete gravity sheet pile, dry dock type) must be used, and for lifts over 50 feet, the only choice is concrete construction with a hydraulically well designed filling and emptying system.

For concrete locks, foundation conditions at a specific site, where the lift is over 10 feet, may determine whether the lock will be designed with: (a) gravity walls supported on soil; (b) gravity walls supported on friction piles; (c) gravity walls supported on end bearing piles; (d) gravity walls on rocks (e) drydock type structure supported on soil (or in rare cases such as Bay Springs Lock, the walls may be anchored to rock): or (f) drydock type structure supported on piles. The six types of designs listed above would not be applicable to all conditions of lift from low to high lift. For example, there is no situation known where a lock with a lift of

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over 50 feet would have to be founded on piles. In some situations there may be a design choice between founding a lock with gravity walls on friction piles, end bearing piles, or using a drydock type design founded on soil. With this situation construction cost is likely to be the determining factor.

Within the last 15 years, because of unusual circumstances, there have been two locks built on the lower Ohio River that are designated as "temporary" locks. The "temporary" 110'by 600' and 1200' locks at Dam 53 and at Dam 52, respectively, are expected to serve until such time as permanent now facilities are available. The maximum lifts at Dams 52 and 53 are 12 feet and 13.4 feet, respectively, which are not too great for sheet pile cellular lock wall construction. The temporary lock at Dam 52 has conrete gate bays with miter gates and the walls between the gate bays are gravel filled sheet pile cells. Structural steel rubbing strips are provided along the lock walls to prevent rupturing the walls. The new lock at Dam 52 is located at the land side of the 600 foot concrete lock. An open flume was built along the landward side of the new lock and openings beween the sheet pile cells connect the lock chamber to the flume. The upper end of the flume terminates in an intake into the upper pool, and the downstream end of the flume discharges into the lower lock approach. A pair of rectangular vertical slide valves are located at the upstream and downstream end of the flume. The operation time for this lock is 20-25 minutes filling or emptying) and lock chamber conditions are somewhat turbulent. Some difficulty was experienced initially with loss of material from some of the cells. Also, the cells are vulnerable to rupture by tows; however, to date there has been no catastrophic accidents at the lock. The temporary lock at Dam 53 is generally similar in design, construction, and operation characteristics. Because of foundation and stability problems with gravel filled cells, the 13.4 foot lift at Dam 53 is probably about the maximum that should be considered for a lock that is planned for 10 to 20 years use. It must also be recognized that where heavy traffic with 10,000 to 20,000 ton tows is involved the element of risk from collision is infinitely greater than with a permanent type concrete lock. If a tow should rupture one or more of the sheet pile cells in entering the lock so that uncontrolled flow developed, the lock would eventually have to be taken out of service, the pool lowered, and the cells replaced. The

ensuing loss to navigation on a waterway as important as the Ohio River would be immense and might disrupt the economy along the waterway. To reduce this danger, sheet pile cells could be filled with tremie concrete instead of gravel and individual cells could be bonded together. The sheet pile cell lock is suitable for low lifts on secondary tributary waterways where tows or vessels are not large (5,000 to 10,000 tons); where traffic (existing and potential) is light; and where interruption to traffic would not constitute a major disaster. Figure III-D shows a sheet pile lock.

The Calcasieu Lock (Figure III-E) in the Gulf Intracoastal Waterway west of New Orleans is typical of "very low lift" earth embankment sector gate locks. This lock is 1,180 feet long, 75 feet wide, has a 13 foot depth on the sills and has a lift of about four feet. Earth embankments serve as lock walls. A concrete gate structure attach end has vertical axis sector gates that form a closure to make up the lock chamber. The earth bottom and the interior side slopes of the lock chamber are riprapped to prevent erosion from propeller wash. Timber guidewalls supported on piles extend along the toes of each of the embankments that have mooring bitts and a walkway for linesmen. The lock is filled or emptied by gradually opening the sector gates. Since sector gates can be opened or closed in free flow and can operate with head in either direction, this type is well suited to conditions in this area. Most of the vessels and tows are not large compared to Ohio and Mississippi River tows as the width of the waterway limits tow width to about 52 feet and length to 1,000 feet. The concrete gate structures are supported on friction piles, and apparently have presented no serious differential settlement problems. The features most vulnerable to damage are the timber guide and guard walls in the lock chamber and at each end of the lock. The first cost of this type of lock is roughly about 25% of the cost of the same size lock with a 20 foot lift and a side port filling system on the Ohio River.

Other simplified less costly types of locks can be designed, but in all cases filling and emptying times will be increased and capacity will be appreciably lower than the capacity of a conventional design concrete lock that can be filled or emptied in six to ten minutes.

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Figure III-D

Ortona Sheet Pile Lock

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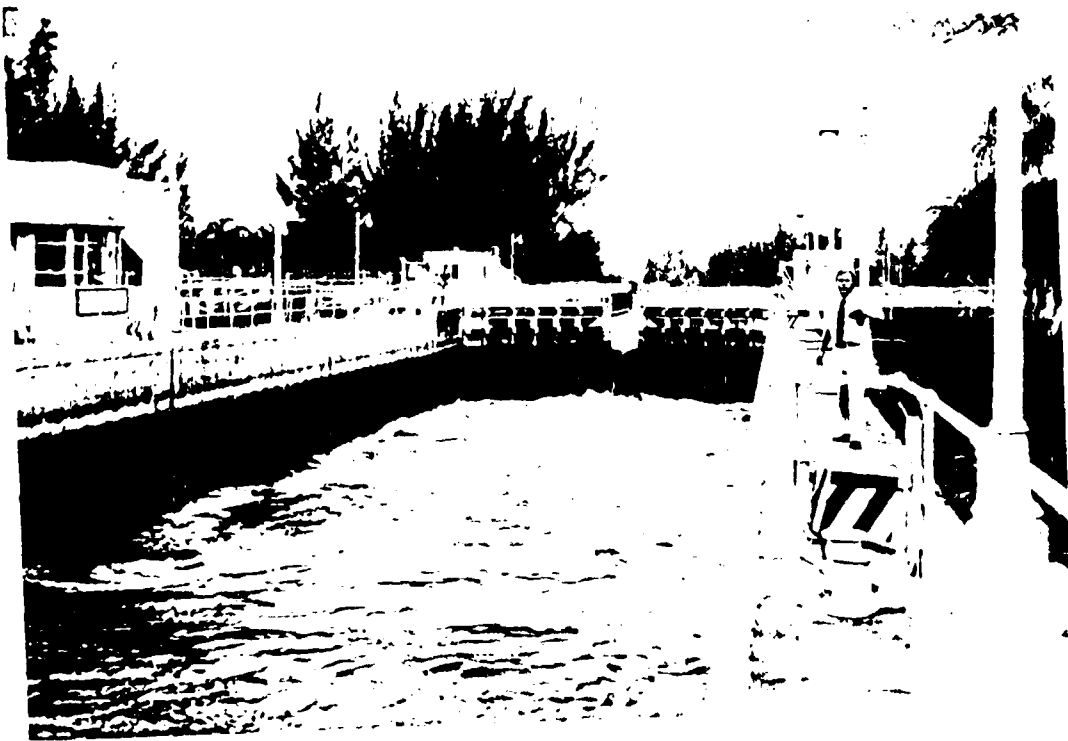
Figure III-E

Sector Gate Lock

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On secondary waterways where lifts are never greater
than 20 feet, where locks need be no longer than 600'x84'
and where low capacity can be accepted, it may be possible
to use a simplified design. Such a lock can be built with
concrete gate bays; miter gates; a loop culvert filling
and emptying system (end filling system and sheet pile
walls). Walers along the top of the walls with tie back
anchorages at the top and concrete struts across the bot-
tom would be used to stabilize the sheet pile walls. The
lock floor would be waved with precast concrete blocks
placed on a suitable 12 inch thick blanket of pervious
material on top of plastic filter cloth. Each of the con-
crete blocks would have relief openings to relieve uplift
pressure. This type of lock would require a filling and
emptying time of about 20 to 25 minutes. Three locks of
this type, in a smaller size, were built on the Pearl
River in Mississippi in 1952. Recently, some considera-
tion has been given to synthetic or fabric dams. Much
more research is required to show the feasibility, relia-
bility and safety of these structures, however.

In the Soviet Union, if lifts are low, light struc-
tures of prefabricated concrete are often used. Long ex-
perience in operating this kind of lock (particularly on
the Moscow River system) proved their high quality as well
as their relative inexpensiveness. In addition, their
rapid construction and convenient mounting are irreplace-
able in rebuilding existing locks which have a strict
reconstruction time schedule (often only three or four
winter months).

In the future, very low lift locks will probably be
built similar to the Calcasieu Lock or the Pearl River
Lock in sizes up to 600'x110'. For sizes larger than
this, for heavier tows, and where traffic density is
greater, concrete construction will probably be required.
For lifts above five feet, on most waterways concrete
locks with the sideport filling system on the bottom
longitudinal filling system will probably be necessary.

(c) Recreational Locks.

At places where recreational craft appear in con-
siderable quantities, the introduction of separate
handling facilities may be worthwhile. Such separate
facilities could be canvas slings or steel tanks to lift

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the craft or groups of craft from one level to another, separate small locks out of the main navigation channel, or a mechanical lift or inclined plane moving lock such as has been used in Europe and in the early canal development in the United States. Certainly, the technology required to construct small conventional locks and small mechanical lifting devices is well established. Separation of recreational traffic from towboat traffic would not only be of assistance in moving waterborne commerce, but would also appear to be a safety improvement.

As part of the 1977 "Recreational Craft Locks Study Stage II Planning Report,"[1] for the Upper Missi.. ippi River, several alternatives for providing separat.. facilities for recreational craft were considered. The.. included the following:

- a 110'x 360' conventional concrete lock.

- a 110'x 400' conventional concrete lock.

- a mobile floating lock.

- a small scale steel lock.

- a small scale concrete lock.

- a differential railway lift.

- a steel tank on inclined rails.

- a steel tar.. lift crane.

- a mobile boat carrier.

- an inclined channel lift.

- an inclined plane lift.

The 110'x 360' or 400' conventional concrete lift would be constructed by conventional means and fitted into the existing site.

A mobile floating lock is a self-contained, fully operational lock structure which can be positioned behind the existing upper miter gates for the auxiliary chamber. This device would be approximately the size of three

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barges abreast (105'x200'). The lock is a steel vessel similar to a dry dock. The sides would be floating tanks housing the operating machinery and controls. The upper and lower gates, integral parts of the lock, would be permanently mounted within the outside tanks.

The small-scale steel lock, 25'x80', would be a double-wall steel structure of 3/8-inch plate with adequate diaphragms. The upper gate bay would include a vertical lift gate and an emptying system. The upper sill elevations would be set to accommodate sailboats up to 40 feet long.

The 25'x80' concreted and sheet-pile lock would be a concrete U-frame structure on a sand foundation. The structure would include a concrete upper gate bay monolith, a lower concrete gate bay monolith, and a lock chamber of sheet-pile walls with a revetment floor. The inside face of the cofferdam would act as the outer form for the concrete gate bay monoliths and would be constructed on site.

The differential railway lift consists of a steel tank (pan) carried up an inclined plane, over a crest, and down a reverse plane without being tilted. The pan is rigidly suspended from a carriage equipped with two sets of wheels to travel on a system of tracks elevated over the earth dike. The outer set of wheels maintains the pan horizontally while the carriage travels above the downstream face of the dike on a 2.5-horizontal to 1-vertical incline. The inner set of wheels maintains the pan horizontally while the carriage travels above the upstream face of the dike on a reverse 2.5-horizontal to 1-vertical incline. Both sets of wheels are used as the carriage travels above the crest on a double set of differential rails.

The steel tank on inclined rails consists of a steel tank (pan) carried up an inclined plane, rotated on a turntable, and lowered down a reverse plane. The pan is rigidly suspended from a carriage equipped with wheels to travel on a system of tracks elevated over the earth dike. The carriage would be propelled by wire rope cables

wound on an electric-hydraulic winch mounted on a turn-table on top of the dike. The turntable would rotate 80 degrees on a circular track to position the carriage for lowering the tank down the opposite side of the dike. No clearance problems are anticipated; however, the boats must depart stern first.

The steel tank lift crane is a steel tank (pan) sup-ported by an overhead crane at each corner. The cranes lift the tank vertically out of the water, travel hori-zontally along rails across the dike, and lower the tank into the water on the other side. The crane trolleys on each rail are structurally separated from the trolleys on the other rail and each uses one drive wheel. The four lift motors and both crane drives are electrically syn-chronized, eliminating overhead clearance restrictions.

The mobile boat carrier system is based on a mobile boat carrier, presently used for launching certain plea-sure craft. The slings could be replaced with a tank (pan) for holding he boats being transported. The modi-fied boat carrier would lift the tank out of the water, travel along a horizontal track across the dike, and lower the tank into the water on the reverse side. The carrier cross member would restrict the overhead clearance. Addi-tional studies would be required to determine if the slings could be safely adapted to various boat shapes.

The inclined channel lift is similar to a device in operation at Montech, near Toulouse, France, connecting two canals. Two water levels in the canal are joined by a 480 foot flume or concrete ramp having a U-shaped section. Water at the upper level is held back by a tilting gate. The boat on the lower level enters the approach basin. A large plate at the end of two arms is lowered into the water behind the boat, forming a wedge-shaped body of water in which the boat floats. The plate is then pushed forward by two 1000-horsepower diesel-electric locomotives, one on each bank.

The inclined plane lift resembles Belgium's Ronquieres ship lift located near Brussels. Barges enter a tank (pan) with gates at either end and are pulled or lowered by electric motors connected to the tanks. Counterweights

run up and down in recesses between the tank rails. The
version considered for the Upper Mississippi River would
have one tank approximately 26'x80' and maintaining a
depth of about four to five feet. The system would be
operated by remote control from the main lock and moni-
tored by television and two-way audio communication.

The only detailed investigation of recreational locks
was performed for the mobile floating lock. A preliminary
design was developed utilizing prestressed concrete
("Recreational Craft Locks Study Selected Alternatives -
Upper Mississippi River"). The lock chamber would be
56'x165' and would accommodate 12 small craft. To conform
to existing channel draft limitations, the lock would be
partially constructed in a shipyard, floated to the
selected auxiliary lock, and completed in place. Filling
and emptying would be accomplished by culverts which would
be part of the mobile lock connected to the chamber by
wall ports. Gates would be conventional miter gates
electrically operated.

The design for the mobile floating lock was selected
partly because of the availability of auxiliary chambers
into which the floating locks could be installed (at Locks
3 to 10 on the Upper Mississippi River).

LAYOUT AND CONFIGURATION
  OF NAVIGATION LOCKS
  AND DAMS

The layout and general arrangement of a lock (or
locks) and dam at a specific site, with respect to river
hydrographic and hydrological characteristics, are the
most critical features in development of inland navigation
projects. Hydraulic model studies and verification of the
model studies with full scale prototype tests, examining
channel levels, river currents and channel depths, are an
absolute necessity if costly mistakes are to be avoided.

In selecting a location for a lock and dam within a
certain reach there are, however, general guidelines which
can be formulated based on practical experience and the
results of research. Since most river channels follow
continuous patterns of curves and reverse curves, with

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very few, if any, short reaches of straight channel, any
lock and dam will have to be located in a curved section
or very close to one. On streams where sediment movement
is not a major factor, such as the Ohio River, the lock
(locks) and the gated spillway section of the dam should
usually (but not always) be located on the concave side of
a very flat bendway or on the side of a naturally straight
reach where the channel is the deepest and the most
stable. The lock should only be located on the convex
side of the river if all other options are investigated
and found inferior. Where a lock is located on the convex
side, river currents will tend to move downbound tows
across the river and toward the spillway during medium and
high flows. This situation exists at Gallipolis Locks on
the Ohio River and Dresden Island Lock on the Illinois
River. At the latter location, a downbound tow has to
turn left through about a 30 degree angle at a point 3000
feet upstream from the end of the upstream guidewall.
This maneuver is time consuming and is hazardous at
times. There are also situations where placing the lock
on the concave side of a bend does not produce satisfac-
tory navigation conditions. If a lock is located near the
downstream limit of a concave bend, in close proximity to
a "crossing" where the natural river current crosses to a
reverse bend, there will usually be outdrafts that move
downbound tows away from the lock. Lock and Dam No. 3 on
the Upper Mississippi River is handicapped by this situa-
tion and also is adversely affected by having about 325
feet of non-overflow dam and the upper end of an unfin-
ished 110 foot wide lock between the existing lock and the
gated spillway. The main flow follows the outside of the
sharp bend to a point about 1400 feet upstream from the
lock and at that point begins to turn leftward toward the
spillway. At a distance of 800 to 500 feet upstream of
the lock, the main current crosses the lock approach at an
angle of 25 to 35 degrees. This situation illustrates the
problems that are created when location of a lock and dam
is governed completely by foundation and structural condi-
tions and points up the need to examine a proposed site in
a hydraulic model.

     If the stream that is being improved carries a heavy
sediment load, such as the Arkansas River, the Red River
in Louisiana, or the Missouri River, selecting a proper
site becomes extremely complex and will require movable
bed model studies. On the other hand, if the stream is
not a heavy sediment carrier, similar to the Ohio, the

Monongahala or the Green Rivers, fixed bed models can be used.

Locks located in landcut canals pose no serious problems to vessels from adverse currents (except the entrances to the canal where current conditions are analigous to currents in approaches to locks at the head of the third wall), but may be affected by wind and canal surges caused by lock filling and emptying.

Filling and emptyin a lock from/into a canal ca.. produce surges varying fror a few tenths of a foot to several feet in water-surface e evation, peak-to-trough, which can adversely affect naviga ion and operation of the lock. The magnitude of the su ge depends on the length, width, and depth of the canal and the volume, rate and frequency of lock filling/emptying operations. Large surges can cause barges to hit the bottom of the canal during the trough of the surge wave if adequate depths are not provided to compensate for its effects and can break moored or waiting vessels loose from their moorings. Currents varying in intensity and direction which cannot always be anticipated by the pilot may also devolop within the canal. The change in the water-surface elevation caused by the surge can also affect the head gate (under some circumstances, reflection of such a surge might cause the upper miter gates to momentarily open). Surges in a canal can continue for several hours, and if sucessive lock fillings occur, the magnitude of the surge can be several times greater than that for a single lock filling. Surge problems exist at Bankhead Lock in Alabama, at the high lift locks in the Welland Canal in Canada, in the Long Sault Canal upstream from Eisenhower Lock in the St. Lawrence Seaway, in the upstream approach to McAlpine Lock, in the downstream approach to Kentucky Lock and at several other locks.

The magnitude of surge in a canal can be reduced by reducing the length of the canal approaching the lock; increasing the cross-sectional area of the canal, particularly depth; using a surge basin near the lock-filling intake; and permitting some river-flow through the canal by providing a ported guard wall on the lock with outlets discharging into the river channel upstream of the spillway.

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The problem at the Welland Canal occurs in the pool between the flight locks and the next downstream lock. Emptying the lock chambers with a 46 foot lift directly into the short canal section between the locks in 10 to 15 minutes would create intolerable surging that would affect vessels in this short canal section as well as filling and gate operation of the next downstream lock. To solve this problem, a separate discharge basin was built adjacent to the canal section between the locks. This discharge basin was separated from the canal by a pervious embankment with enough openings to permit flow from the basin to the canal at a slow enough rate to minimize surge effects. When the last locks of the parallel flight locks are emptied into the basin, there remains in those lock chambers an increment of water about three to five feet above the canal level. At that point in the operation, other valves are opened to discharge this last increment of volume directly into the canal. This system has worked very well to date. (Note: Flight locks are a series of locks built very close to each other so that a series of small locks act as one high lift lock. Where it is possible to put the locks very close together, the filling and emptying systems can be interconnected so that the emptying operation for one lock serves as the filling operation for the next lower lock. In some cases, the downstream gate of one lock could also be the upstream gate of the next lock. In longitudinal profile, these locks resemble a staircase. The Panama Canal is a good example of this type of lock.)

Where it is necessary for a canalized portion of a waterway to descend an escarpment or a precipitous drop, questions arise as to whether the descent should be made: with flight locks, with several low lift locks separated by short intermediate pools or by a single high lift lock. No general conclusion or rules to govern such a selection can be developed because, terrain, capacity and other features will differ from site to site. There are, however, factors to consider that will point the way to a proper selection for a specific site. Locks with lifts very much in excess of 100 feet, say 120 to 140 feet, experience difficulties in design and operation. Cavitation at the valves and other hydraulic and structural problems become critical. Locks with lifts in excess of 100 feet are operating satisfactorily. If topography is reasonably favorable, a difference of 140 feet in elevation should be accomplished by two separate locks of 60 to 80 feet lifts,

with an intermediate pool. (The final selection, however, should be based on economic considerations as well as technical feasibility.) The intermediate pool should be long enough to allow vessels to safely pass so that one-way traffic would not be necessary, and wide enough to diminish crosscurrent and surge. Further, problems associated with discharging into and filling out of the intermediate pool would have to be worked out to avoid surging problems. The third possibility, use of flight locks with two or three locks in tandem, is about the least attractive of any of the three possibilities. Unless two sets of flight locks (twin flights) are provided, a tow entering from one direction, preempts use of all of the locks in the flight and a tow moving in the other direction must wait until the entering tow has cleared the second or third chamber of the flight of locks. As a result, lock capacity is significantly reduced. Other complications exist also. For a flight of three lock chambers in tandem, the total lift must be divided into three equal increments and culvert valve operations must be carefully controlled with failsafe interlocks to prevent flooding of the lower lock chambers. Flight locks can be considerably less expensive, however, than equivalent lift separated locks.

At locations where it becomes necessary to build two locks, based on the results of model studies, two layouts have been developed which when adopted at future sites should provide safer and more efficient movement of traffic through the locks. The first layout uses adjacent locks and the second uses separated locks.

With two adjacent locks of the same size, there is a common intermediate wall. The general practice has been to equip the river-side (main) lock with a ported upper guard wall and a solid upper guide wall on the landside lock. When the upper guard wall is ported, tows tend to be moved toward the guard wall because of flow through the ports, making it somewhat difficult for downbound tows to approach the guide wall for passage through the land-side lock. Another problem confronted with this arrangement is that a tow cannot safely approach either lock when another tow is leaving or tied up along the guide or guard wall, resulting in delay for approaching or departing tows.

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Figure III-F

Layouts for Two Locks at a Site

(a)

(b)
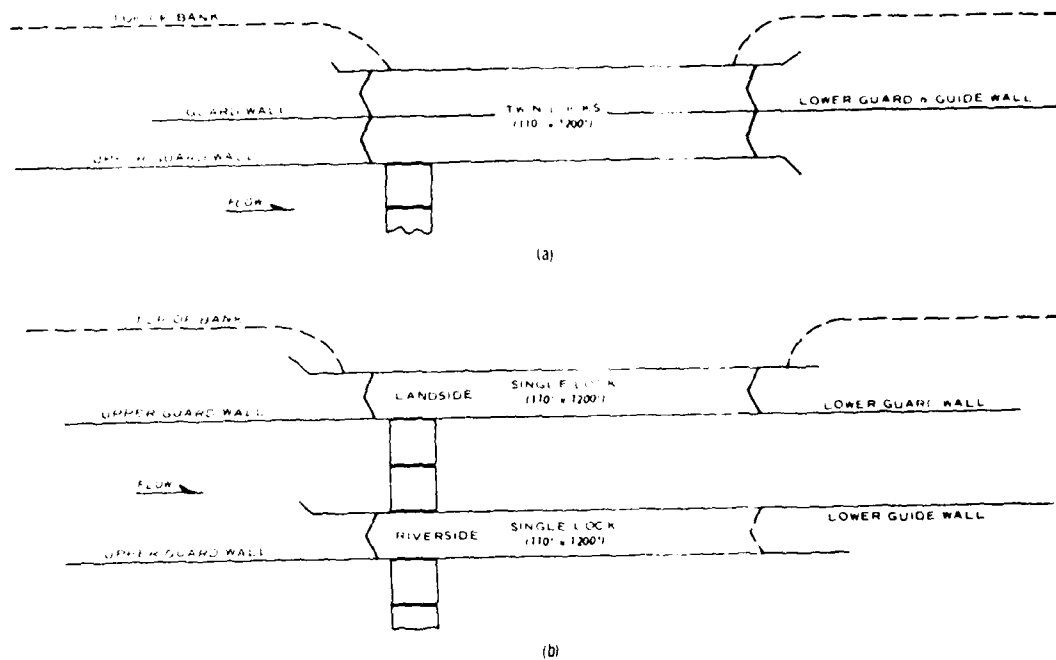
A preferred arrangement is to provide an upper guard wall for both locks when the locks are adjacent (Figure III-F(a)). Both guard walls would have to be ported. The land-side guard wall should be at least half the length of the usable portion of the lock chamber and the river-side guard wall should be of sufficient length to extend at least three-fourths of the length of the usable portion of the lock chamber beyond the end of the guard wall for the land-side lock. These lengths are based on limited tests with specific projects and some variations might be desirable, depending on local conditions. Since there would generally be little flow through the ports in the land-side lock guard wall, the tops of the ports should be a few feet higher than those in the river-side wall to develop currents that would assist tows in approaching the upstream wall. As a result of this arrangement, a downbound tow could approach the river-side lock and be followed by a downbound tow approaching the land-side lock as soon as the tow using the river-side lock has landed along the guard wall. Also, a downbound tow using the land-side lock can approach the lock while an upbound tow is leaving the river-side lock.

In the lower approach, the intermediate wall would be used to form a guide wall for both locks. With this arrangement, tows entering or leaving one lock would not interfere with tows entering or leaving the other lock. For safe two-way traffic, the length of this wall should be the same as that of the tows using the locks. In addition to the advantage of two-way traffic, a long intermediate wall would cause a more gradual increase in channel width than with a long river-side guard wall, thereby reducing the shoaling tendency and, in turn, maintenance cost and interference with traffic during maintenance dredging.

The second layout involves separation of the locks to provide two-way traffic in either or both directions (Figure III-F(b)). The amount of separation required is presently a matter of opinion and could vary depending on local conditions, but suggestions range from 1.5 to 3.0 times the lock width. A number of projects have been built in The Netherlands in recent years with twin lock chambers that were separated by considerably more than an intermediate wall and provided enough space to permit simultaneous movement of vessels into and out of both locks.

If two 110 foot wide locks are separated by 1.5 lock widths (165 feet) there would be about 435 feet of river channel closed to normal flow. In a river about 1200 to 1500 feet wide, this amount of lost flow space can create very undesirable outdrafts and crosscurrents in the upper lock approach. To reduce the effects of the obstruction, spillway gates can be provided between the locks to pass some of the flow affected by the locks. This would reduce the crosscurrents produced by the total flow moving toward the spillway across the riverward lock approach. The size and intensity of the eddy that would be developed in the lower approach would also be reduced since the amount of channel expansion would be reduced. Upper guard walls would be required on each lock. The lengths of the upper guard walls should be at least three-fourths of the length of the usable lock length, depending on the currents existing after completion of the project. In the lower approach, the guide wall could be on either side of each lock. The length of the guide wall on the landside lock should be at least half the length of the usable lock chamber and on the river-side lock at least two-thirds of the length of the lock chamber.

The latter arrangement (separated locks) was studied in model studies for the proposed new Locks and Dam 26 on the Mississippi River at Alton, Illinois. The initial construction will provide only one 1200'x110' lock, but the project is planned and designed so that a second 1200'x110' chamber can be added when needed without major modification to any of the principal features. A picture of what the proposed structure at Locks and Dam 26 will look like after construction of the initial lock is shown in Figure III-G.

Lock separation could also be accomplished by placing locks on both sides of the channel with the gated spillway between the locks. This arrangement would be ideal for two-way traffic and would be preferred by navigation in- terests. However, in most streams it would be extremely difficult to develop currents in both lock approaches that would not be objectionable to navigation, particularly during higher flows. In addition, sediment accumulates on the convex side of bends which could cause a maintenance problem on some rivers.

Figure III-G

Proposed Layout for Locks & Dam 26
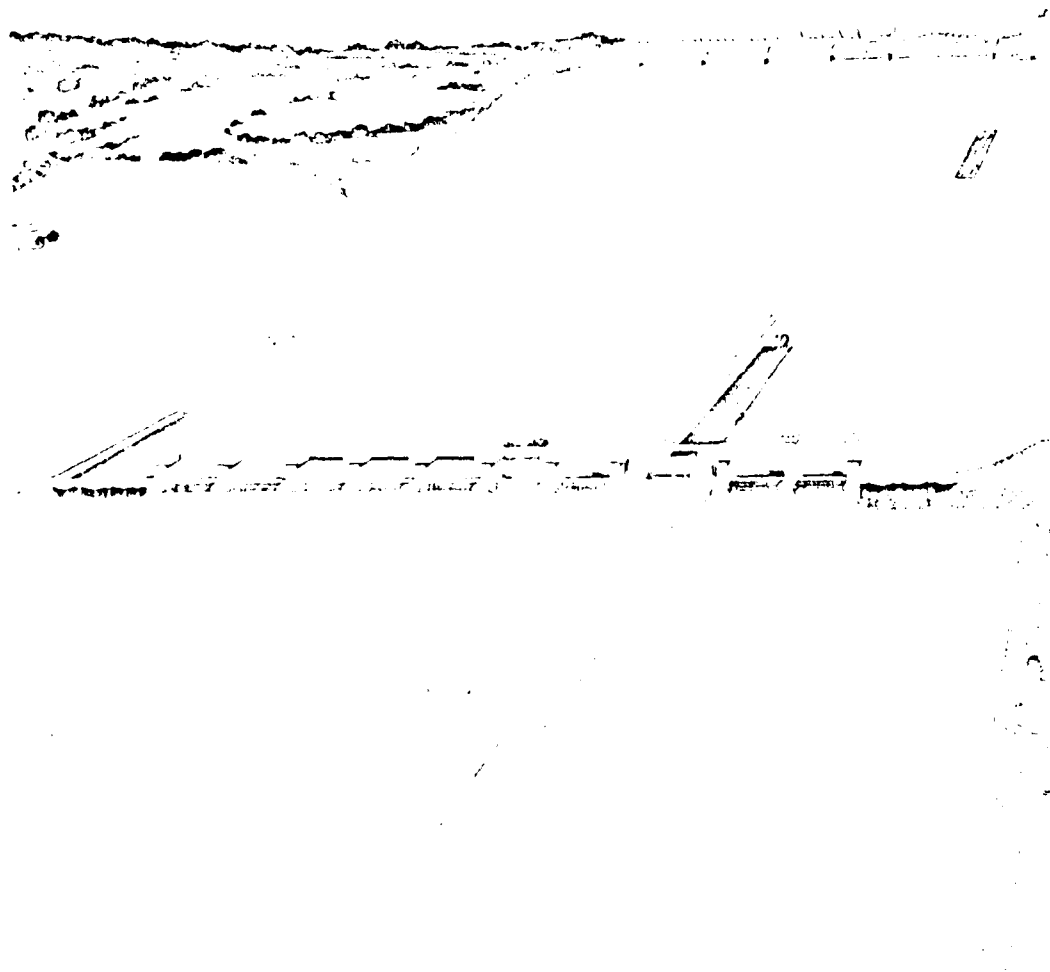
Particular attention has to be given to the layout of a lock that is being placed in a dam where hydropower is a main feature. The lock must be located so that flow to the powerhouse as well as to a spillway will not create adverse currents in the lock approaches. This may sometimes require either a long dike or a separate channel in the upper pool leading to the lock. It may also be necessary in some situations to build a long guard wall or separating dike in the lower pool to keep random surges and general turbulence from creating bad navigation conditions downstream of the lock. In development of the Rhine River in France for hydropower and navigation, the channel leading to the lock was separated from the channel to the hydro plant for about one kilometer upstream and for about 0.5 kilometer downstream. Most, but not all, of the multipurpose projects built recently in the United States have the lock on one side of the river and the power house on the other side. Where locks and hydropower have both been included in the initial planning of a project, the upper pools have been fairly deep and large, since hydropower have both been included in the initial planning of a project, the upper pools have been fairly deep and large, since hydropower for heads less than about 30 feet were not considered economically worthwhile.

With deep and large upper pools, few problems from adverse currents have developed. Unfortunately at the Bonneville Project on the Columbia River, the upper lock approach conditions are very poor and dangerous. The peculiar orientation of the dam and powerhouse was selected initially in order to found the structures on rock. By doing this the flow to the powerhouse crosses the upper approach channel at an angle of 20 to 30 degrees with surface velocities of five to six feet per second. Many accidents have occurred. Plans for a new lock have been developed by means of model studies that will minimize the adverse conditions.

For fiscal year 1981, several work units have been proposed by the Waterways Experiment Station of the Army Corps of Engineers that will address problems associated with means to minimize the effect of hydropower releases on navigation.

LOCK SIZES IN RELATION TO
CHANNEL DIMENSIONS AND
TOW SIZES

In Section V (Table V-1), the minimum recommended safe channel widths for two-way traffic are presented for various tow sizes. From another point of view, that table presents the maximum size tow which can safely navigate a channel of any given width (with some additional widening in the bendways). The maximum width of channel which can be economically maintained depends on the morphological and hydrological characteristics of the waterway. Thus, on the Upper Mississippi River where controlling widths (i.e., minimum segment width) are 300 feet, the common maximum tow size is 15 jumbo barges (35'x195') and on the Alabama River, where controlling widths are 150 feet, the common maximum tow size is two jumbo barges. (Note: the minimum safe channel widths are somewhat lower than the recommended minimum safe channel widths if the number and frequency of restrictive reaches is low so that one-way traffic in the restricted reaches is possible without seriously delaying traffic. See Section V.

On most waterways, many tow operators find it more economical to size their tows to fully occupy the minimum safe channel dimensions (between locks). Thus, tows arriving at the locks are of sizes which range up to the maximum size (length and width) which can safely navigate the channel. Locks which can accommodate tows of the maximum size which can safely navigate the channel rarely have double lockages, nor would they be expected to. Locks which cannot accommodate tows of the maximum size which can safely navigate the channel experience frequent double, and in some cases triple, lockages. It stands to reason, then, that the maximum lock size (length and width) which would ever be required on a waterway would be a size which could accommodate the maximum size tow (length and width) which can safely navigate the waterway channels (or a lock which could accommodate more than one vessel/tow at a time).

In the subsection "Lockage Time in Relation to Lock and Tow Characteristics" design recommendations for optimum depth over the lock sill are discussed based on requirements for safe and timely vessel entry and exit. Just as the lock width restricts the maximum width of tows

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which use the waterway, the depth over the lock sill also limits the maximum draft to which vessels may load. The minimum depth over the sill which would be required on waterway locks would be a depth which would safely pass the maximum draft vessels which the waterway channel can accommodate. However, additional depth over the lock sill will increase the speed and efficiency of tow entry and exit of the lock facility.

The discussion of the previous three paragraphs leads to consideration of the most complex problem in waterway planning. Waterway locks, once constructed, have a very long working life (greater than 50 years) and are very expensive to replace. Lock dimensions provided on a waterway should, therefore, theoretically be adequate to accommodate traffic for the life of the structure. In practice, however, the capacity of a lock may be exceeded well before the useful life of the structure has been reached. Depending on the limiting physical dimensions of the lock, the lock may have to be replaced by a larger lock excluding other, possibly less costly, methods to increase capacity. For example, if lock dimensions are provided at the time of construction which can accommodate tow sizes which cannot be accommodated by the channel but which could be accommodated by the channel if additional channel improvements are implemented (i.e., widening, straightening of bends and deepening), then overall savings might be achieved. In other words, locks which can accommodate a higher level of traffic could be built but channel modifications to accommodate that level of traffic could be deferred until higher traffic levels develop. The best example of this type of planning is the depth over the lock sill provided at the time of construction. If a depth over the sill is provided allowing very efficient lockage times with current channel depths, the depth provided may also be sufficient to handle more deeply loaded tows with adequate safety, if project depths are increased, albeit with a reduction of locking efficiency. It should be noted that increasing project depths by one foot (from 9 feet to 10 feet) can increase waterway capacity by up to approximately 10% by allowing tows to load deeper. As a practical example, locks along the Ohio River will accept 12 foot draft tows although project depths are only nine feet. It may, therefore, be more economical to increase project channel depths (by raising pools, dredging or a combination of

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both) than to replace the existing locks or add auxiliary chambers when additional capacity is required.

It should be noted, also, that the relationship between tow size and safe channel dimensions is somewhat dynamic. Historically, as the horsepower of towboats has increased, with resultant increased maneuverability, the common maximum sizes of tows on the waterways have also increased. There may still be some room for increases in tow sizes if economics were to shift towards still more powerful towboats, especially if waterway improvements such as easing of bends, elimination of restrictive reaches and lock replacement were undertaken. In addition, if future industry improvements were to include such items as bow steerers or "automotive coupled units" (see Section IV) tow maneuverability would be improved and tow sizes may increase somewhat.

LOCK SIZE SELECTION AND STANDARDIZATION

Throughout the historical development of canalized waterways in the United States, lock sizes have been influenced more by vessel sizes and by the desires of operators to use the maximum size vessel or tow that was practical than by any other factors. Early navigation on the Ohio River brought about the first general use of the 600'x110' size lock that is still the size most widely used today. When this size lock was adopted in 1878, a width clearance of 14 feet and a length clearance of 110 feet was available (for a typical coal tow of that era made up of ten 130'x24' barges, a 230'x48' steamboat and a fuel barge 110'x22'). In the ensuing years, barges have become larger, towboats have become generally smaller, even though power has increased and the original clearance between tows and locks has shrunk to the extent that in some instances there is only two feet of width clearance and 10 feet of length clearance.

The 110 foot width is still the maximum width lock in use in the United States today. Length has increased from 600 feet to 700, 800, 1000, and 1200 feet, which is presently the maximum. Since the 110 foot width was adopted

100 years ago, builders and operators of barges and tow-boats have designed their vessels to work in fairly reasonable harmony with locks of this width.

It would appear that rational selections of a maximum size lock, at the present, should be governed by (a) the maximum size tows that could use the waterway (two-way traffic) without excessive channel improvement work; (b) the type of towing equipment in general usage; (c) the expected amount of traffic; (d) economic; and (e) lock sizes on connecting waterways. Strangely enough, the 110 foot width selected over 100 years ago appears to have met, very well, the above requirements, as tow sizes and barge sizes have grown to fit existing lock widths.

Even though the 600'x110' and 600'x84' sizes had become somewhat of a standard by 1960, there were still many locks being built of different sizes. The locks built on the Columbia-Snake River systems from 1950 to 1976 were 86 feet wide an 675 feet long. This size was chosen to suit towing equipment in use on the Columbia, Willamette and Snake Rivers, which are completely isolated from the waterways of the central part of the country.

In the same period, a number of locks 75 feet wide and of varying lengths were built in the Gulf Coast area. The 75 foot width was influenced by narrow inland canals along the Gulf Coast which have widths of 125 to 200 feet. The canal widths limited the tow widths and the tow widths influenced the selection of lock widths.

In the early 1960's attempts were started to fix certain standard lock sizes to prevent a continued proliferation of sizes. The sizes recommended for commercial locks are:

- 84'x 400'

- 84'x 600'

- 84'x 720'

- 84'x1200'

- 110'x 600'

- 110'x 800'

- 110'x1200'

Further needs for lock sizes will continue in the 84 to 110 foot widths and 400 to 1200 foot lengths. There appears to be little need at the present time for shallow draft locks larger than the 110'x1200' size.

NAVIGATION LOCK DESIGN

(a) Filling Systems

The objective in design of a lock filling system is to transfer by gravity flow the water required to fill a volume represented by the area of the lock chamber multiplied by the lift as rapidly as possible without causing damaging surges or turbulence. The criterion used to guage the effects of surging is the amount of stress or pull produced on the mooring lines of a vessel during a filling or emptying operation. Lock filling operations normally cause the greatest turbulence and maximum hawser stresses. For operating conditions with barge tows, the maximum permissible design value that is used in the United States and in Austria is five tons. The five ton value is based on the working stress of 2.5 inch diameter used manila hawsers, assuming that tows would be moored with two such lines. Through many model tests, filling system designs have been developed that meet this criteria in the models. This does not mean that a prototype hawser stress in a prototype lock will be limited to exactly five tons. What it does mean is that through experience with many locks that were model tested, the prototypes perform very satisfactorily with no surging or turbulence that would swamp small craft, when these locks were based on model tests utilizing the five ton hawser pull criterion. However, in the models, it is impossible to get any reliable and consistent hawser pull measurements if the model tow is moored so that horizontal forces acting on a model tow, the tow is mounted so that only vertical movement can occur, i.e., horizontal movement of the tow is completely restrained insofar as possible. Thus, the effects of strain that would occur in mooring lines is not reflected in the measured horizontal forces on the tow. It is

recognized that in the model tests, the effective elimination of strain in the mooring attachments will tend to produce higher stresses than will occur in the prototype if model and prototype are subjected to identical forces of very short duration.

Very little research has been performed in the United States to evaluate hawser stresses as a function of filling type, mooring type (fixed or floating), hawser type (rope or cable), tow size, tow draft or tow tie-up location within the chamber. (With the exception of the design curves for 100'x600' locks (Figure III-I and 110'x1200' locks for the sideport filling system where an attempt has been made to correlate several of the parameters.) With sideport filling systems improper operation of the lock can cause hawser stresses of many times the design value whereas bottom longitudinal systems are less sensitive to operating procedures and hawser stresses normally stay within an accepted design range.

In the Soviet Union where both fixed (with lifts less than 20 feet) and floating moorings are used with steel hawsers, the following formula is used to determine the maximum allowable longitudinal hawser force:

$$E_{max} = 0.3W^{1/3}$$

where W is the displacement tonnage of the largest vessel, fully loaded, expected to use the lock. For a typical (largest) 5000 ton vessel, this provides an allowable longitudinal stress of about five tons. The recommended allowable lateral hawser force is .5 E_{max}. The formula is presented for comparative purposes.

Lock filling systems should be designed to fill and empty as rapidly as possible recognizing the importance of the waterway, comparative costs of different filling systems and the capacity required. On very heavily used waterways, smulation model tests have shown that every minute that filling and emptying can be reduced will usually create benefits in excess of any increase in costs, within certain limits. A filling time of six to ten minutes can usually be achieved, depending on the size of lock under design and the lift, without serious increase

in cost. On the other hand, to try to fill a 30 foot
lift, 1200'x110' lock in three to four minutes would en-
counter problems and costs that would make the project
excessively costly, if such a goal could be attained.
Filling and emptying times that can be obtained without
excessive costs are:

1.	very low lift and low lift locks	6 to 10 minutes
2.	intermediate lift locks	7 to 10 minutes
3.	high lift locks	8 to 12 minutes

(Refer to Figure III-O in the report "Engineering Analysis
of the Waterways System.)

The simpliest, least expensive type of filling and
emptying system is known as an "end" filling system - it
has been given this designation because the lock chamber
is filled or emptied by flow into or out of one end. The
lock is filled by gradually opening the lock gates; open-
ing valves in the gates; or opening valves in culverts
("loop culverts") that pass from the upstream side of the
gates to the dowstream side. There are various other
combinations involving loop culverts and programmed gate
opening schedules, but since all of the water enters or
leaves the chamber at one end, there is no way to overcome
all surging effects. Any end filling system for a given
size and lift of lock will always require a greater fill-
ing and emptying time for a given mooring line stress than
any of the other systems.

Some additional research may be worthwhile to investi-
gate the hydraulics of end filling systems as they are
likely to continue to be economically viable alternatives
for very low lift locks in intracoastal and harbor loca-
tions where tidal effects are very low.

The wall culvert side port system has longitudinal
culverts in the lock walls that extend from an intake up-
stream from the upper gates to a discharge outlet down-
stream from the downstream lock gates. Each culvert usu-
ally has a filling valve located downstream from the upper

lock gates and an emptying valve upstream from the lower lock gates. The section of each culvert between the filling and emptying valves is connected to the lock chamber by a series of short water passages known as ports. In a filling operation the emptying valve in each culvert is closed; the filling valves are opened; and water flows from the upper pool into the culvert intakes and into the lock chamber via the culverts and the ports. With this system, flow into the lock chamber is distributed fairly well over the whole lock chamber and surges and turbulence are held to no-damaging conditions. However, this system can be made to perform satisfactorily for lifts not much greater than 30 feet, with acceptable operation time. It has been model tested for lock lengths of 600 and 1200 feet and widths of 84 and 110 feet. It is currently the most widely used system in the United States, since most of the locks built in the past 40 years have had lengths of 600 and 1200 feet, widths of 84 and 110 feet and most of the lifts are not greater than 30-35 feet. While the 30 foot lift limit mentioned above is generally valid, there are situations where lifts infrequently become greater than 30 feet for very short durations. Port Allen Lock, for example, has a maximum head of 45 feet. This situation does not necessarily preclude use of the side port system, because during the high lift occurrences, operation time can be temporarily increased to avoid unacceptable turbulence conditions in the lock chamber. Figure III-H shows a sketch of a side port filling system. The depths of water in the lock chamber, or cushion depth as it is called, is a very sensitive factor in design of a side port system. Through an exhaustive model testing program, design curves have been developed for three sizes of locks that define the relation between the following parameters (Figure III-I):

- Lift   (only 10 to 50 feet)

- Filling Time

- Submergence Depth

- Hawser Stress

By use of these curves and other data obtained in the model studies, side port filling systems can be developed for a lock of any lift (in the 10 to 40 foot range) in three sizes without resorting to model tests (at lifts greater than 40 feet or with unusual conditions, model

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Figure III-H

Side Port Filling System
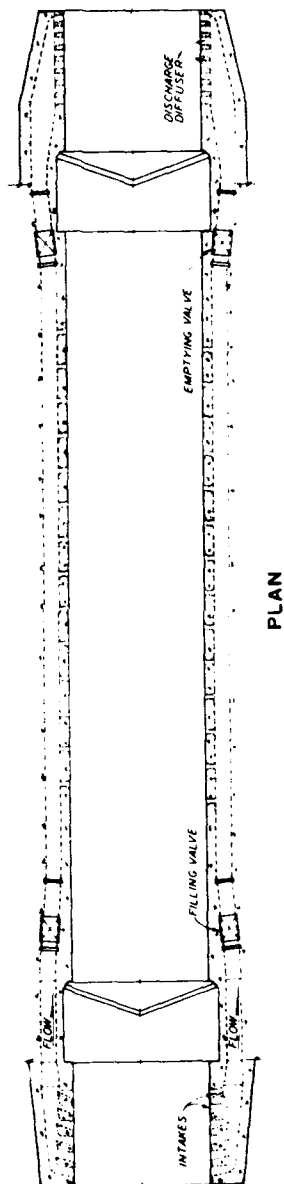
PLAN
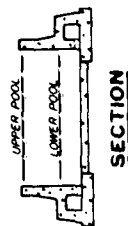
SIDEWALL PORT

SECTION

Figure III-I

Design Curves for 110 by 600 ft. Lock
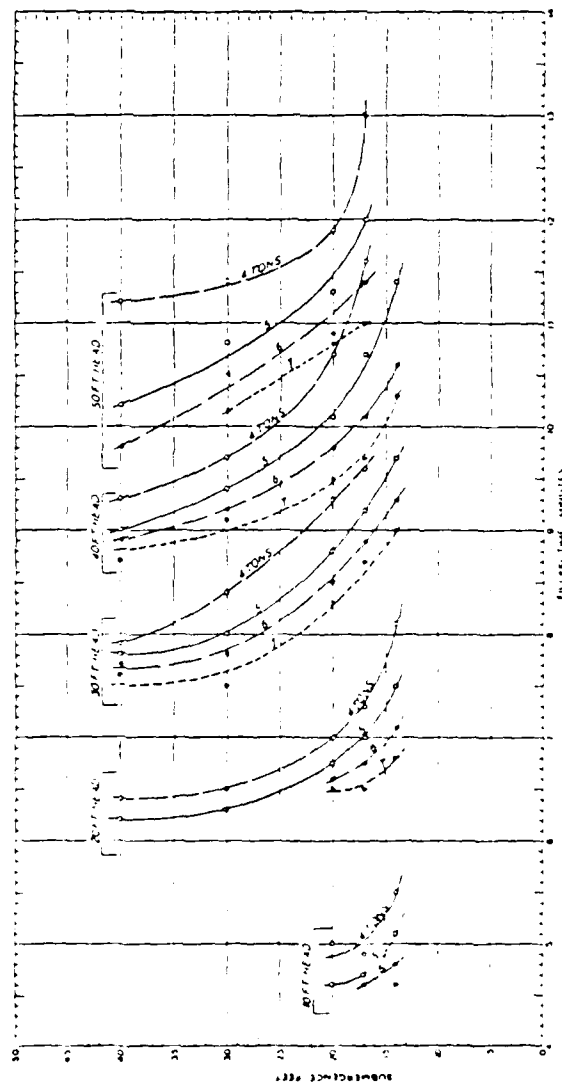
MODEL STUDY OF LOW LIFT LOCKS ARKANSAS RIVER

HAWSER STRESSES DURING FILLING

TYPE A PORT   TYPE 6, ARRANGEMENT

SOURCE: Corps of Engineers, WES.

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studies may still be desirable). Figure III-H, however, cannot be taken as a final recommendation as local conditions may allow or require variation.

TVA, in the early 1960's, developed a variation in the sideport system which was designated as a "Multiport system," (Figure III-J) In this design, the rectangular ports (with 8 to 10 square feet of area for each port) were replaced with a large number of 8 or 10 inch diameter pipes. The Corps tested this system and found it to have no advantages over a conventional side port system -- structurally, hydraulically or in terms of cost.

For lifts greater than 30 feet, on important waterways, the side port system is generally unsatisfactory for barge locks as the required operation time becomes too great. Prior to the 1960's, a system utilizing main wall culverts (as in the side port system) and transverse culverts across the bottom of the lock with ports had been developed and used on high lifts. This system was an improvement, in some respects, over the side port system, but still left much to be desired as a satisfactory distribution of flow into the lock chamber could not be obtained. Figure III-K shows the layout of a split bottom lateral filling system and Figure III-L shows the layout of an interlaced bottom lateral filling system.

A system known as "bottom longitudinal culvert" system was developed for locks with lifts over 30 feet and has proved to be a vast improvement over the other systems. In this system, main wall culverts and valves, essentially the same as with the side port systems, are used. But, instead of connecting the wall culverts directly to the lock chamber via ports or transverse culverts with ports, flow from the wall culverts enters a cross culvert at the mid-point of the lock chamber and is then discharged into longitudinal culverts on the lock floor extending upstream and downstream from the cross culvert. Flow is discharged into the chamber via ports in the longitudinal culverts. This arrangement provides a much better distribution of flow between the upstream and downstream portions of the lock chamber and reduces hawser stresses and turbulence. The critical feature of the system is the connection of the cross culvert to the main wall culverts. In the first version of this system, a vertical dividing wall was

Figure III-J

Multiport Filling System

PLAN

CENTER LINE LOCK

CULVERT

CULVERT

FLOW

FLOW

INTAKE MANIFOLDS

OUTLETS IN RIVER

LOCK WALL

TRENCH

CULVERT

PORTS

TYPICAL PORT SECTION

UPPER POOL

LOWER POOL

SECTION

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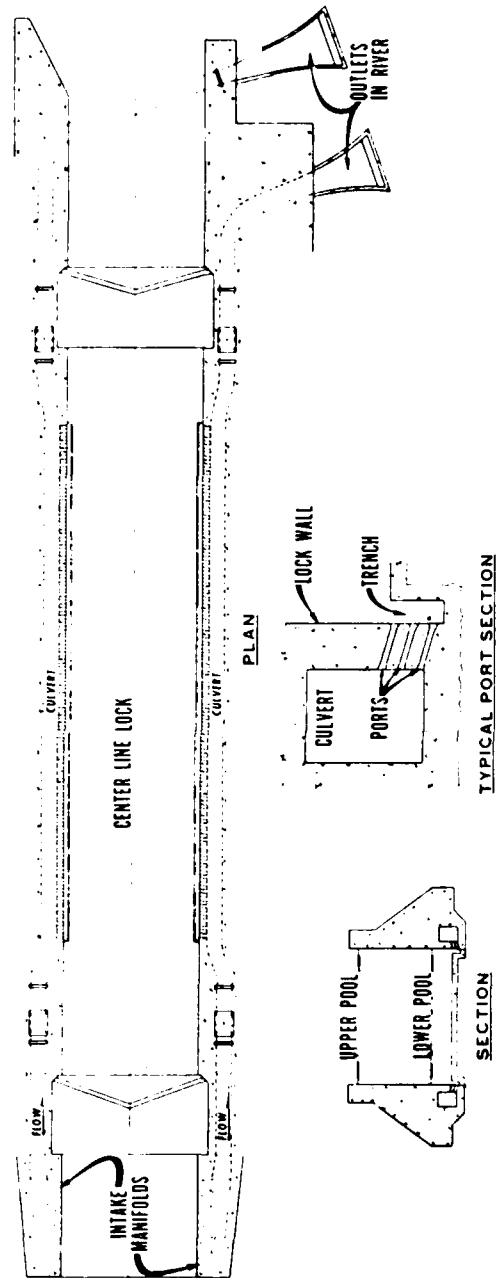
Figure III-K

Split Bottom Lateral Filling System
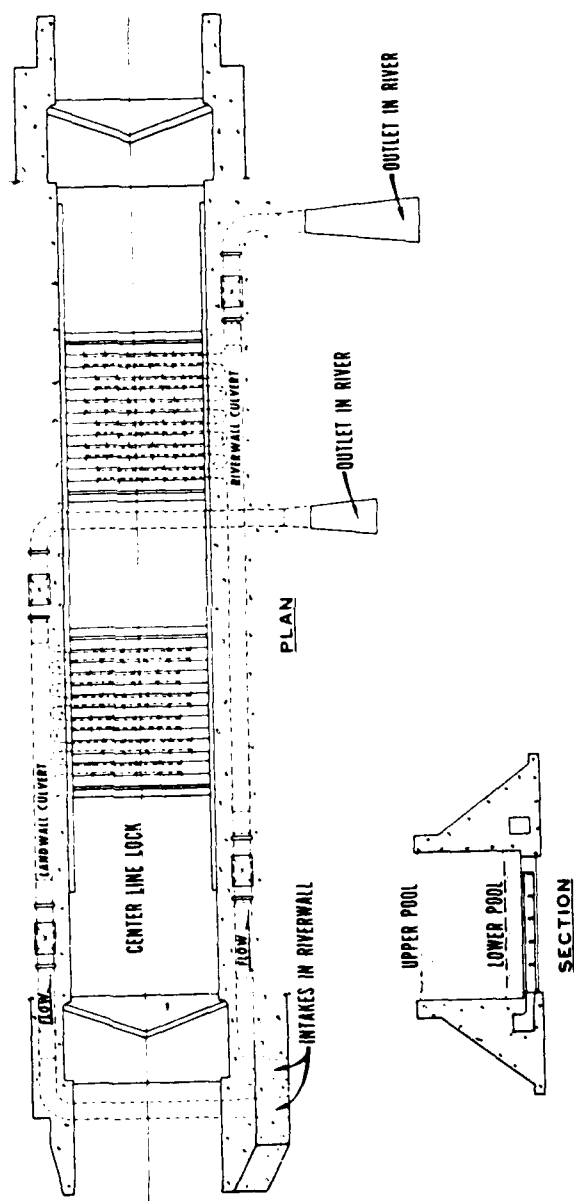
Figure III-L

Interlace Bottom Lateral Filling System

PLAN

SECTION
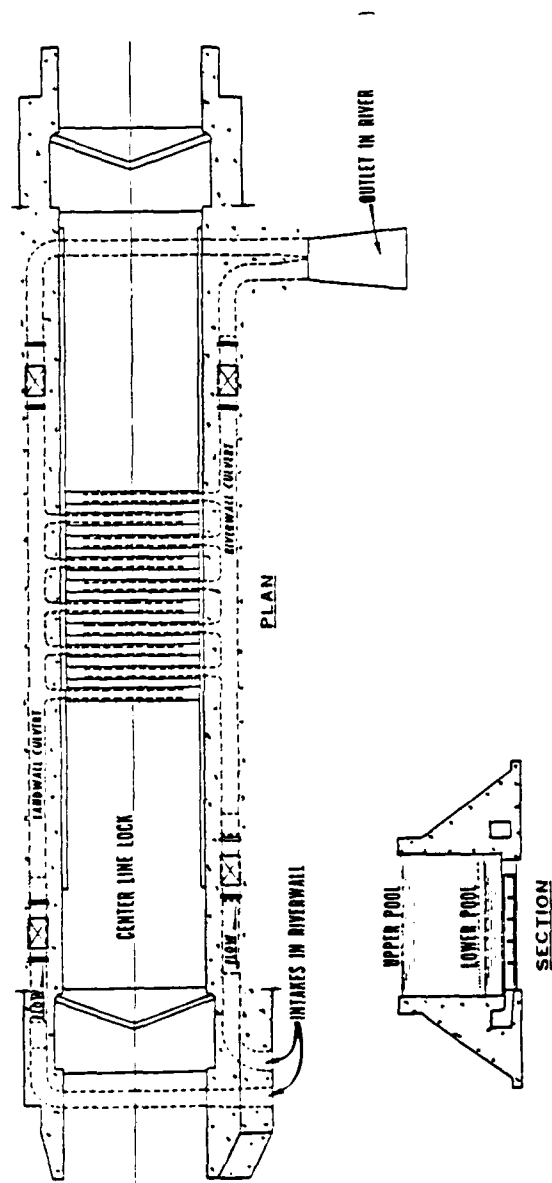
placed in the cross culvert to split the flow between the upper and lower halves of the lock chamber. Turning the flow 90 degrees (from the main culvert) and dividing it at the same location will not produce an even division of flow. However, again within limits, an approximation of flow division can be obtained that produces reasonably satisfactory results for 600 foot locks with lifts up to about 70 feet.

A much better version of this system has been developed wherein the flow division is accomplished by a horizontal diaphram placed at mid-height of the wall culvert immediately before the flow is turned toward the mid-point of the lock. This system achieves an almost perfect 50-50 split in discharge to the upstream and downstream halves of the lock chamber. This system, coupled with a four branch manifold in the bottom of each half of the lock chamber can be made to perform satisfactorily for lifts up to and over 100 feet with lock sizes of up to 110'x1200'. The system provides equal flow distribution with either valve operating alone and is not affected by non-synchronous valve operation. In the design for one lock that utilizes this system, there are 48 ports in each half of the lock chamber and flow begins simultaneously at eight of the 48 ports. The eight ports where flow begins first are arranged so that there are four ports at the approximate quarter point of the lock (length). Surges propagated by the initial inrush of flow are attenuated by mutual interference. Figure III-M is a diagram of a bottom longitudinal filling system.

Thus far, there have not been enough locks built using bottom longitudinal system to allow their design without model studies. Thus, high lift locks to be constructed in the foreseeable future will require hydraulic model testing of the filling system in order to assure satisfactory design.

As has been developed in the foregoing paragraphs, research during the past 20 years has fairly well defined the limitations of the four types of filling systems that appear to be best for United States waterways. These systems are:

    1. end systems.

Figure III-M

Bottom Longitudinal Filling System

PLAN

SECTION

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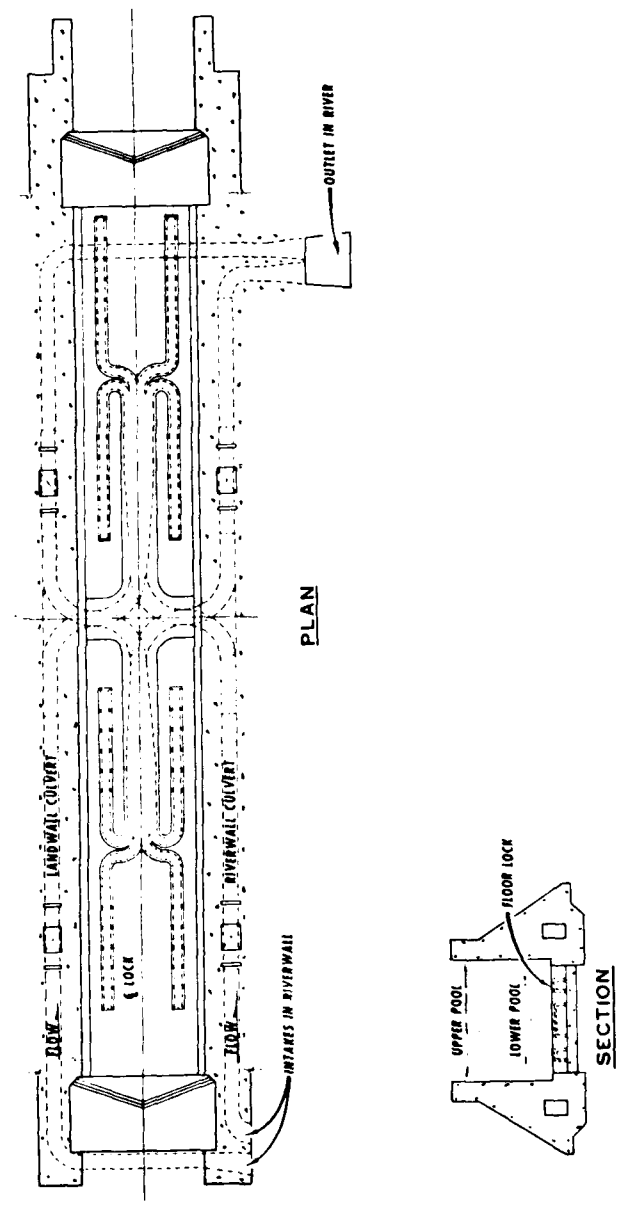
2. horizontally split bottom longitudinal
systems.

3. vertically split bottom longitudinal systems.

(b) Valves

Eight different types of valves have been used to control flow into and out of lock chambers. These eight general types are listed below:

- slide valve.

- wagon valve.

- stoney valve.

- buttlerfly valve.

- vertical cylindrical valve.

- tainter valve.

- reverse tainter valve.

- horizontal cylindrical valve (Howell Bunger).

The first three types are all flat rectangular shutters that differ in the way they are retained and moved over, and removed from the culvert opening. Slide valves move vertically in recesses with metal surfaces and are so named because the metal valve body slides on metal strips in the recesses. This type is relatively simple but usually requires frequent maintenance because of wear on metal to metal sliding surfaces.

With the wagon valve or "wheeled valve," as it is also known, the rectangular shutter is mounted on small wheels that ride in recesses in the culvert wall thd there is no metal to metal sliding. A rubber sliding seal is provided to prevent leakage. This type also requires frequent maintenance because of wear on the wheels, and tracks in the recesses. Vibration can also become a problem because of the clearance required for the wheels.

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The stoney valve has lengths of small articulated free running rollers (similar to a length of bicycle chain) between the rectangular shutter and metal lined recesses in the valve shaft. The valve bears against these rollers and when it is being raised or lowered, the rollers directly transmit the horizontal load to recesses in the valve shaft. This arrangement reduces friction and consequently the force required to raise or lower the valve is greatly reduced. The sides are sealed by means of sliding rubber seals attached to the valve body. Old designs of this valve were subject to serious vibration problems, and excessive wear on the valve recess tracks. It is possible that improved designs of this valve could be developed.

A butterfly valve has the flat shutter mounted on a shaft that runs across the midsection so that the shutter can be rotated from a position that completely closes the opening to a position wherein the shutter is parallel to the flow in the culvert. In this position, it offers very little obstruction to flow. In some respects this type of valve is simple in construction and operation. For low heads it can be used without real difficulty. However, it creates serious disturbance to flow patterns in the culvert which becomes quite serious in high head installations for locks. Maintenance is costly and designs for high heads are difficult.

Vertical cylindrical valves were used at some of the higher lift early locks, but are now considered to be obsolete. They are prone to destructive vibration, tend to suck in unwanted air and require continuous maintenance. This type valve has not been built in the United States since the late 1920's.

The tainter valve (with the skinplate upstream) has been used at a number of locks on the Upper Mississippi River that were built during the 1930's. This type of valve is rugged, simple in design and does not require continuous expensive maintenance. But, its principal disadvantage is a serious one; it permits large volumes of air to be drawn into the filling culverts, with normal operation, which can cause unacceptable turbulence. This disadvantage led to development of the reverse tainter valve in which the valve is positioned with the skinplate

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Figure III-N

Tainter Valve. - McNary Lock
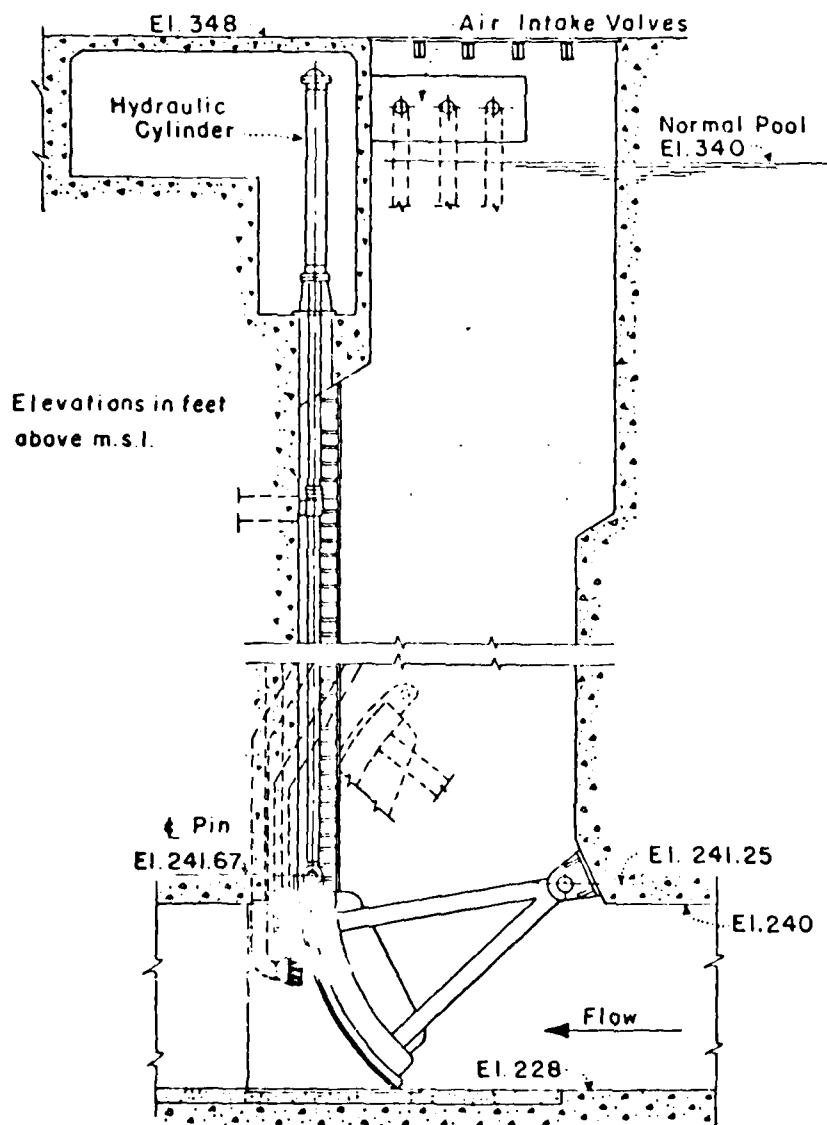
downstream. Figure III-N, shows a section through a reverse tainter valve.

The reverse tainter valve was developed in about 1937 to provide the advantages of a tainter type valve but without the disadvantages of pulling air into the culvert system. It has proven to be be the most trouble free, the most rugged and the least costly from a maintenance standpoint of any of the types previously discussed. The side seals are of rubber, and once they are properly adjusted, require very infrequent attention. The top seal is also rubber, but is a make and break compression seal. In operation, the water in the valve well remains at the upper pool level when the valve is closed or when the valve is open and the lock chamber level is coincident with the upper pool elevation. The valve well thus serves as a surge basin or tank during the valve opening period to relieve intermittent surging in the culvert system upstream from the valve well and to prevent entrance of air into the culvert as the valve is opened. This type valve has been widely adopted in the United States for all concrete locks in the low and high lift classification with side port, bottom lateral or bottom longitudinal systems.

Different designs for reverse tainter valves have been developed and used since 1937. The most successful design to date is the design developed during model studies for Holt Lock. This valve is a single skinplate vertically framed valve that reduces random uplift and downpull forces to a minimum.

Some trouble was experienced initially with the trunion anchorage at some of the high head locks. These problems were readily corrected and the designs revised accordingly so that no further trouble has been experienced. Trunion bearing cap wedges should be provided for all intermediate to high lift locks (Bay Springs for example).

The horizontal cylindrical valve (Howell Bunger type) has not been used for a lock anywhere in the United States. It has been used in Russia for the emptying culverts on a high head lock - 130 foot lift - where flow is not discharged into the downstream navigation channel.

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In summary, only slide valves, butterfly valves and
reverse tainter valves have been used on locks built in
the United States in the last 40 years. There are a few
very low lift locks on secondary waterways where slide
valves and butterfly valves have been used. As noted
above, most of the locks have reverse tainter valves.

Part of the success of reverse tainter valves comes
from their generally satisfactory operation at high
heads. This has, in fact, facilitated the development of
high lift locks in the United States. Currently, a design
manual for reverse tainter valves is being prepared at the
Waterways Experiment Station of the Army Corps of Engi-
neers, however, additional work is required in order to
improve the usefulness of the manual for design purposes.

In future lock construction, reverse tainter valves
will probably be used more than any other type. Excep-
tions to the use of the reverse tainter type valve may
occur with end filling systems and possibly water saving
basin locks and where other types of valves exhibit par-
ticular advantages (the final choice of valves should be
left to the designer). Butterfly valves and slide valves
can be used for very low lift locks and slide valves de-
signed for head in either direction may be necessary for
water saving locks.

(c) Gates

There are nine different types of lock gates in use in
the United States and in Europe. These nine different
types are:

- miter gates.

- submergible vertical lift gates.

- overhead vertical lift gates.

- submergible tainter gates.

- vertical axis sector gates.

- rolling gates.

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- horizontal axis sector gates.

- bottom hinged gates.

- single leaf vertically hinged gates.

Miter gates are used at more United States locks than any other type. Some locks have miter gates at one end and submergible tainter gates or vertical lift gates at the other. Combinations involving overhead vertical lift gates at the downstream end and either submergible tainter or submergible vertical lift gates at the upstream end have also been used recently.

Miter gates are relatively simple in design, are rugged and have given excellent service. The largest miter gates are at Wilson Lock on the Tennessee River where the lift is 100 feet and the lock width is 110 feet. Each gate leaf weighs 1,300,000 pounds; is about 114 feet high and 65 feet wide. Miter gates at locks built in the last 15 years are designed to open in one to two minutes; are horizontally framed; and have upstream skin-plates. Some difficulty has been experienced when miter gates were subjected to temporary reverse heads of 1 to 2.5 feet. Reverse heads force the gates open and then when they slam closed, they do not always miter properly. When a subsequent filling of the lock subjects the improperly closed gates to the design head, one leaf may fold over the other and cause complete failure. In recent years, miter gates have been designed to resist reverse heads of 2.5 feet and the operating machinery designed to hold against a minimum of 1.25 feet of reverse head. This criteria prevents accidents from overfill and underfill of the lock chamber and from random negative surges in the lock approaches. Work is being performed to try and control overfill and overempty of locks so that reverse heads on miter gates will be eliminated. Up to the present, no miter gates have been used on any lock wider than 110 feet. However, in Panama Canal studies of 1970, and in studies of a lock at New Orleans, Design Engineers concluded that miter gates could be built for locks in the range of 150 to 185 feet in width. There is shown in Figure III-O a picture of a miter gate for a lock.

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Submerged vertical lift gates have been used as service gates at the upstream end of Locks 19 and 27 on the Mississippi River and at the John Day and Lower Monumental locks. Several of the new Ohio River locks utilize submergible vertical lift gates as a means of emergency closure at the upstream end of the locks. Submergible vertical lift gates for service gates have not proved to be as trouble free or as desirable as other types (Figure III-P).

Overhead vertical lift gates have been used at the downstream end of John Day, Ice Harbor and Lower Monumental Locks and at the upstream end of Lockport Lock on the Illinois Waterway. The lifts at John Day, Ice Harbor and Lower Monumental Locks are over 100 feet. With lifts of this height the downstream gate does not have to extend up all the way to the top of the lock walls. A transverse concrete breast wall is built across the lower end of the lock chamber that extends downward for a distance of 30 to 40 feet and the vertical lift gate is only required to close the opening between the top of the gate sill and the bottom of the transverse concrete breast wall. The vertical lift gate then becomes somewhat similar to a vertical lift sluice gate with a rectangular port. One of the principal advantages of this arrangement arises from the fact that the concrete wall acts as an impact barrier for downbound vessels. There is much less change for an out-of-control vessel to knock out the concrete breast wall than for such an accident to rupture the downstream gate (or gates). Vertical lift gates can be designed to function satisfactorily with reverse heads of several feet where the accompanying sill depth is not too great. They can also be designed to operate under a head of several feet. The overhead vertical lift gates at John Day, Ice Harbor and Lower Monumental Locks can be raised or lowered in about two minutes. Some difficulty was experienced in fabrication of the gates and in the initial operating procedures. However, the gates are performing very satisfactorily at present. Overhead vertical lift gates are used in France, Belgium, Netherlands, Germany and Austria in sizes up to about 80 feet and for lifts from 25 to 80 feet.

Submergible tainter gates have been used at the upstream ends of the Dalles, Little Goose, Ice Harbor and Lower Granite Locks on the Columbia and Snake Rivers and

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at the Lower St. Anthony Falls Lock in Minneapolis. This type of gate is quite successful and can be used where the lift is great enough to permit the gate to be positioned on the downstream side of the upper lock sill when the gate is in the lowered position. That is, neither a submergible tainter gate nor a submergible lift gate can be positioned in a recess in the bottom of the lock chamber. There would be a continuous and troublesome maintenance problem in keeping debris out of the recess. When in the lowered position, the bottom of a tainter gate should be no lower than the bottom of the lock chamber. Head reversal from overfill is not a serious problem and this gate can be designed to operate in flowing water if necessary. There is shown in Figure III-Q a submergible tainter gate. Operational times must be evaluated carefully when substituting submergible tainter gates miter gates or other type gates.

There are more than 15 locks in the United States that have vertical axis sector gates (Figure III-R): Almost all of these locks have lifts in the "very low" to "low" range. Sizes range from 1000'x110' to 120'x30'. Sector gates possess some unique advantages that other gates do not have. A sector gate may be conceived of as a sector of cylinder standing on end. This sector is designed to rotate about the vertical axis of the sector and when two such sectors are arranged to rotate in unison and meet along a vertical line at the center of the lock they can act as a closure of gate. If the gates are properly designed, all hydraulic forces are always directed toward the vertical axis of the sectors and regardless of whether the head is from upstream or downstream there are no forces acting to open or close the gates. Thus sector gates can be opened or closed in free flow conditions and operate with a head from either side. This feature is of particular advantage in the Gulf Coast area where tide and wind conditions can occasionally produce a reversal of head. Sector gates have also been used as guard gates at some places.

The rolling gate is a shutter that rolls horizontally on rails from a recess in one side of the lock across the lock to close the lock chamber. This type of gate was used first on the original 110 foot wide locks on the Ohio River. The last Ohio River lock with these gates was

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Figure III-O

Lock Miter Gate

Lower Miter Gate diagram with labels including: Lock Chamber, Lower Gate Bay Wall, Culvert Discharge Wall, Lower Approach Wall, Trunnion, Light Standard, Gate Anchorage, Wall Armor, Gage, Safety Markings, Check Post, Lower Pool, Bulkhead Recess, Bulkhead Sill, Temporary Closure (Bulkheads), Lock Emptying laterals, Culvert Bulkhead Recess, Lower Valve Pit, Lower Culvert Valve, Walkway, Miter Gate Recess, Lock Filling and Emptying System, Side Po, Bottom, Lower Gate Sill, Unpaved, LOWER MITER GATE (HORIZONTALLY FRAMED)

Figure III-P

Submerged Vertical Lift Gate

Nappe in max raised position

H.W. El. 437.67 2

Top of wall El. 432.0 7

MAXIMUM RAISED POSITION OF GATE

Spillway Crest El. 403.0

El. 401.0 Limiting Pool El with D.S. Leaf only raised

DOWNSTREAM LEAF

Flow

30'-0"

8'-2"

Sill El. 374.0

10'-3 5/8"

Gate - 110' Wide

UPSTREAM LEAF

30'-0"

Gate rest El. 344

Floor El. 343.67
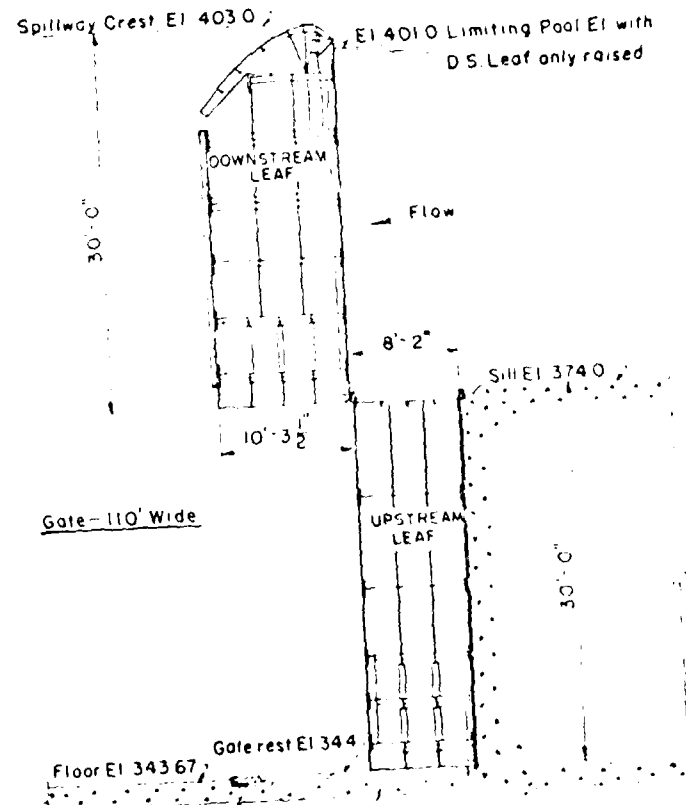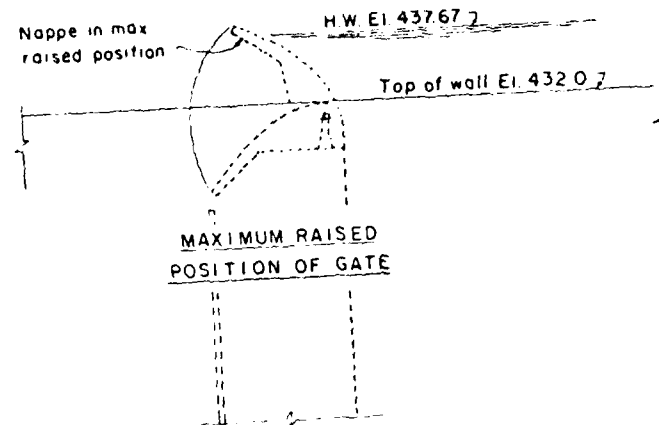
Upper Lock Gate. - Lock No. 27. - Mississippi River

Figure III-Q

Lock Tainter Gate. - St. Anthony Falls
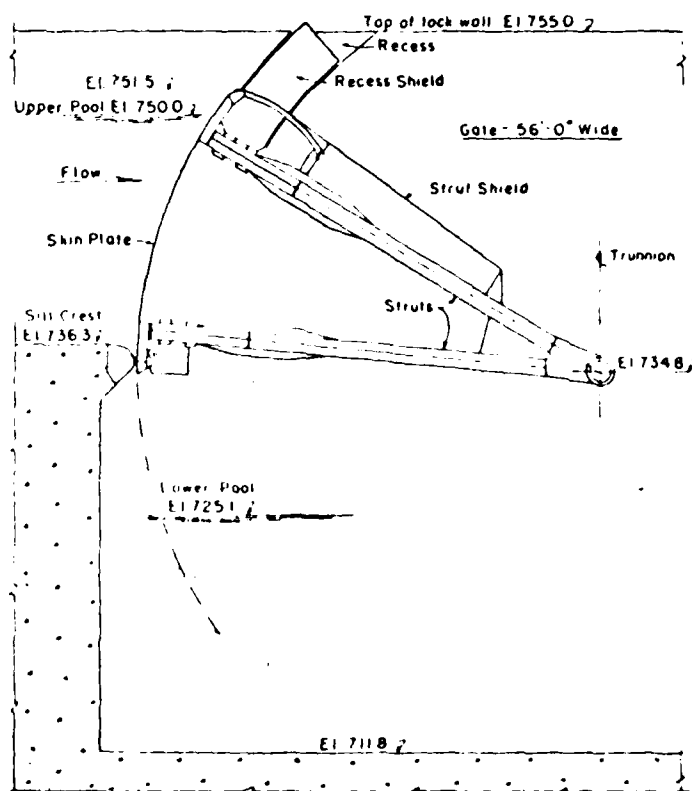
Figure III-R

Sector Gate Lock

GATE PINTLE

RECESS

GATE

CENTER LINE LOCK

PLAN

FLOW

GATE PINTLE

RECESS

GATE

UPPER POOL

LOWER POOL

SECTION

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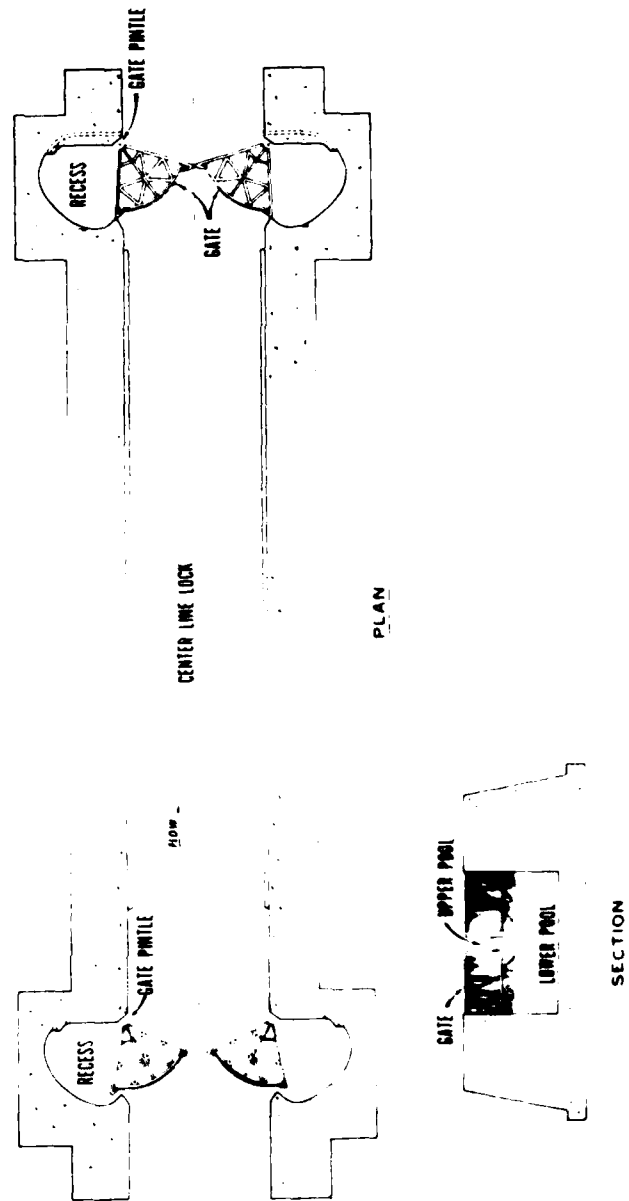
taken out of service about ten years ago. They were uti-
lized for the 110 foot wide locks at the turn of the cen-
tury because at that time engineers did not favor miter
gates this large. This type of gate is rather widely used
in Europe. A fairly new maritime lock in Belgium that is
1600 feet long and about 186 feet wide uses this type of
gate. When these gates were used at the original Ohio
River locks, there were continuous troubles and expensive
maintenance problems. After every open river period, the
gate recesses and gate tracks would accumulate silt and
mud that had to be washed out before the gates could be
operated. This type gate is considered obsolete in the
United States.

A sector type gate with a horizontal axis has been
used in Europe for locks with widths of about 40 feet and
lifts of about 20-25 feet. This same general gate type
has been adopted by Great Britain for flood gates on the
Thames River downstream from London. These gates span an
opening about 214 feet wide and have a daming height of
about 35 feet. Consideration has been given to this type
of gate for a lock 150 feet wide and 40 feet deep, but
because of deflection and consequent leakage with possible
vibration problems the gate does not appear to offer any
advantages for a lock gate.

Bottom hinged gates have been used successfully for
dry docks and have been used at one old lock (1934) in the
United States. This type gate is a plane rectangular
shutter that is attached to the sill by horizontal hinge.
The one presently in use is raised and lowered by hydrau-
lic cylinders that actuate strut arms. There are no par-
ticular advantages to this type of gate and a number of
serious disadvantages. Possible damage from dragging an-
chors; inability to fully lower the gate because of
debris; and lack of accessibility for maintenance are some
of the drawbacks.

There are several old small locks in Europe that have
single leaf vertically hinged gates. A gate of this type
is essentially a door at the end of the lock chamber and
is so called in Holland. There are no such lock gates in
the United States. Their only advantage is simplicity
when used for very small locks.

For the foreseeable future, most of the lock gates in
the United States will probably be miter, vertical axis
sector, submergible tainter or overhead vertical lift
types (lower gates only). For very high lift locks, sub-
mergible tainter gates and overhead vertical lift gates
may find application. For very low lift locks, either
miter gates or sector gates may find application.

(d) Approach
     Channels

The time required for a tow to approach a lock and
become properly aligned to begin the lockage process is,
at most locks, a very significant portion of the total
lockage time. In recognition of this fact, a great deal
of effort has been historically placed on designing ap-
proach channels to eliminate difficult approach conditions
and thus minimize lock service times. The primary diffi-
culty encountered in developing designs for lock ap-
proaches has been due to the complexity of the parameters
involved. During the approach the tow must slow to avoid
ramming lock walls. This, of course, decreases the tow's
maneuverability, increasing its susceptability to cur-
rents. Identifying currents which will come into being
after construction of new facilities, and developing
methods to eliminate them under the full range of poten-
tial flows that may be experienced at the site usually
requires substantial analysis (either physical model
testing or math modeling).

Locks placed in the channel of a stream form an ob-
struction to a portion of the flow of that stream. The
effects of these structures on currents depend principally
on the configuration and alignment of the channel upstream
and downstream and the amount of contraction and expansion
in channel width produced by the obstruction. The usual
effect of the sudden channel contraction in the upper ap-
proach to the locks is an outdraft or crosscurrent. The
intensity of the crosscurrent is dependent on the total
discharge affected by the structure and is a function of
the velocity of currents approaching the structure, chan-
nel depth, and width of channel affected by the structure,
and, in some cases, by flow along the adjacent overbank.
Since no two reaches of a stream are identical, the inten-
sity of the crosscurrents in the upper lock approach will
vary according to the site selected and the orientation of

the structures with respect to the alignment of the chan-
nel and currents.

Because of the sudden expansion in channel width down-
stream of the lock or locks, a tendency for an eddy to
form in the lower lock approach will exist. The eddy pro-
duces currents moving landward at its downstream end, up-
stream currents along its landward side, and currents
moving riverward at its upstream end. A tow moving toward
the lock with little or no rudder power because of reduced
speed and upstream currents is affected by these currents
which are constantly varying in size and intensity. Cur-
rents in the lower approach can also be affected by lock
emptying, powerhouse releases, uneven gate operation, flow
from or toward the overbank, and flow from tributary
streams. Conditions vary at each site and cannot be fully
resolved by analytical means.

Auxiliary walls are generally provided to assist tows
in becoming aligned for lockage. Guard walls are usually
on the river side of the locks and guide walls are usually
on the land side. The auxiliary walls are generally
placed parallel to and continuous with the lock walls as
planed or angled walls would increase the flow intercepted
by the lock. Guide and guard walls can be placed in vir-
tually any combination or can be of any length depending
on local conditions. In general, at least one of the
walls in each pool is equal in length to the lock chamber.
The upper and lower (long) guard walls should be on the
same side of the lock. This would help to accommodate
double lockages which may become necessary during the life
of the lock due to increased traffic (locks shorter than
1200 feet). In-line walls facilitate the use of tow
haulage units without having to deal with time-consuming
setovers.

Traditionally, lock auxiliary walls have been con-
structed monolithically of concrete. In the upper pool a
solid upper guard wall creates crosscurrents near the end
of the wall which would tend to move the head of downbound
tows riverward and put them in danger of hitting the end
of the wall. It has been found that these crosscurrents
can be reduced or eliminated by permitting all or a major
portion of the flow intercepted by the guard wall to pass
through ports placed in the guard wall. Upper guard walls

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built in recent years have been constructed from either
concrete piers or sheet pile cells capped with concrete so
that ports can be accommodated. The ports are placed well
below the elevation of the bottom of loaded barges in
order to prevent tows from being pulled towards the wall
and are sized to have a total cross-sectional area equiva-
lent to the cross-sectional area of the approach channel
affected by the lock. The distribution and size of port
openings can be adjusted for local current conditions and
to help control sedimentation and debris in the upper lock
approach. However, more studies are required to optimize
the elevation of the ports. Specifically, the full effect
of changes in currents due to the tow itself (because of
the great size of the tow with respect to the size of the
channel) is not fully understood. In addition, it may be
desirable to incorporate shutters on some type of control
gate on the ports so that the port openings could be
varied as local conditions warrant. Concrete panels with
stop log fillers have been proposed in the design of
Smithland Lock.

Solid lower guard walls provide protection from cur-
rents resulting from spillway discharge, uneven gate
operation, powerhouse releases and lock emptying outlets
located on the river side of the lock. Where the effect
of currents in the lower approach are expected to be neg-
ligible, floating booms supported on concrete piers can be
used in place of more costly concrete guard walls.

Differences in depth in the approach channel can
affect the movement of tows in the approach, particularly
if the tow is moving at reduced speed from deep to shallow
water. Tows moving along a bank and passing from a deep
to a shallow portion of the channel block a portion of the
flow in the shallow channel causing a higher water level
to develop between the tow and the adjacent bank that
could move first the head and then the remainder of the
tow riverward. The effects of changes in depths can be
minimized or eliminated with submerged dikes or groins
located some distance upstream of the lock walls. Sub-
merged groins (dikes) can also be used to reduce veloci-
ties in the approach. The elevation and spacing of the
groins would depend on channel depths and current direc-
tion and velocities. In previous studies, groins with
crests 20 feet below normal upper pool elevation spaced
one to one and one-half times the length of the upstream

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groin have proved satisfactory. Dikes that are too high above the bed or spaced too far apart will tend to produce turbulence with erratic currents extending to the surface. These currents are usually local and have little or no effect on the movement of tows approaching or leaving the lock. The disturbance can be reduced by closer spacing of the dikes or by filling between dikes. A fill of the same elevation as the dikes would not be as effective in reducing velocities because of the reduction in channel roughness.

Overbank flow moving toward the river from the adjacent bank or from the river toward the adjacent bank can produce serious crosscurrents. This condition can occur with a low overbank and an embankment blocking downstream flow or with a low overflow embankment with high ground upstream causing some flow toward the overbank. This condition can be eliminated or reduced by constructing a fill or dike along the adjacent bank extending from the dam or locks far enough upstream where tows can either avoid the currents created by the flow or maintain speed and rudder power required to overcome the effects of these currents.

Shoaling in the lower lock approach is a problem encountered at most structures located in sediment-carrying streams. The seriousness of the problem increases with the amount of sediment moving in the stream and will vary depending on the characteristics of the stream, particularly as affected by variations in the discharge. Dredging in the lower approach is costly and interferes with traffic using the lock. Model studies have indicated that a properly designed wing dike extending from the end of the riverward lock wall and angled slightly riverward can reduce the frequency and in some cases, the amount of dredging. The dikes are designed to permit the sediment-free surface flow to move over the top of the dike and thus prevent or reduce the amount of the sediment-laden bottom current moving into the approach channel around the end of the dike. Optimum wing dike design heights, lengths and alignments require model study for the specific site conditions. Incorrect designs can be ineffective.

In the lower approach, the effects of eddies and crosscurrents due to powerhouse releases can sometimes be

eliminated by construction of a long rock dike angled riverward on the river side of the lower guide wall. Model studies are required to determine the proper height and alignment for site conditions, however.

At some locks the upper approach condition can sometimes be improved by placing guard cells angled toward the center of the river upstream from the river guard wall. These cells would be spaced so as to prevent a tow or small boat from passing through the space between the cells but far enough apart that the water flow would pass through them. The cells would provide tows protection from being swept by the current around the end of the river guard wall and into the gates of the dam. The angle of cells should be such that tows will have an adequate maneuvering area for approaching the locks.

With two adjacent locks of the same size, there is a common intermediate wall. The general practice has been to equip the river-side (main) lock with a ported upper guard wall and a solid lower guard wall. The land-side (auxiliary) lock usually has an upper guide wall (land-side of the lock) and a lower guide wall.

A more efficient arrangement of lock walls is possible. A preferable arrangement is to provide an upper guard wall for both locks when the locks are adjacent. The greatest benefit from this arrangement comes from reduced interference between chambers. Both guard walls would have to be ported. The land-side guard wall should be at least half the length of the usable portion of the lock chamber and the river-side guard wall should be of sufficient length to extend at least three-fourths of the length of the usable portion of the lock chamber beyond the end of the guard wall for the land-side lock. These lengths are based on limited tests with specific projects and some variations might be desirable, depending on local conditions.

Separation of locks, which has been found helpful in providing efficient two-way traffic, would produce a greater obstruction to flow and result in an increase in crosscurrents in the lock approaches. To reduce the

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effects of the obstruction, spillway gates should be pro-
vided between the locks to pass some of the flow affected
by the locks. This would reduce the crosscurrents pro-
duced by the total flow moving toward the spillway across
the riverward lock approach; the size and intensity of the
eddy that would be developed in the lower approach would
also be reduced since the amount of channel expansion
would be reduced. Upper guard walls would be required on
each lock. The guard wall would be on the river side of
the land-side lock and could be on either side of the
river-side lock depending on flow conditions and configu-
ration of the channel upstream of the lock.

Locks located in a canal bypassing the dam in the main
channel should be provided with guide walls to assist tows
in becoming aligned for entrance into the lock. Since
there are generally little or no currents in the canal,
walls can be shorter than those required in the main
channel, particularly with a single lock. When twin locks
are located in the canal, guide walls can be provided as
shown in Figure III-S. This arrangement should be less
costly than separate guide walls for each lock and would
permit two-way traffic under most conditions because of
the separation provided by the center wall.

Figure III-S

Twin locks with common guide walls
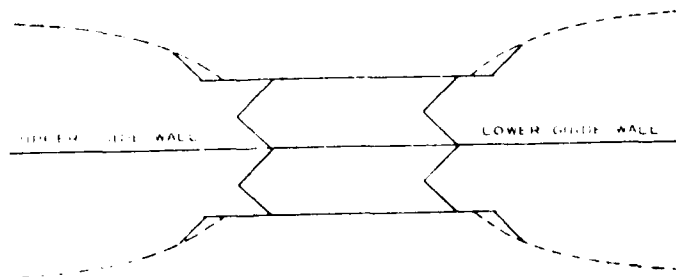
Most of the improved design concepts discussed thus
far have come about as a result of model studies of locks
within the last few years. Most of the existing locks in
the United States were constructed much earlier, however.
As a result, poor approach conditions currently exist at

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some locks which could have been mitigated if the modern techniques had been available at the time of construction. For many of these locks, improvements may be possible by modifying the existing approaches. Possible modifications include:

1. realignment of approach channels.

2. realignment or modification of the auxiliary walls.

3. installation of river training structures.

4. installation of submerged dikes.

5. installation of guard cells angled towards the center of the river from the upstream end of the river guard wall.

6. extension of the auxiliary walls.

7. installation of wing dikes.

8. provision of mooring cells.

9. elimination of obstructions.

10. elimination of debris.

11. reducing the effect of filling and emptying or powerhouse operations.

The purpose of the above improvements would be to bring existing approach channels in line with modern standards. Ideal approach conditions would permit fully loaded tows to become aligned for approach into the lock some distance upstream of the lock and then drive or drift toward the guide or guard wall with little or no maneuvering or engine reversal required.

In Europe, where most locks are located in canals, rather than adjacent to the dam in the river, as in the U.S., angled or flared auxiliary walls are placed in both the upper and lower pools. The walls serve a dual purpose in that they mechanically guide the tow into the lock from the waiting area through physical contact and they aid in

optically aligning the tow. A guiding structure with good optical characteristics is felt to have a favorable effect on locking capacity, because it encourages higher entry speeds (the potential decreased safety should also be considered).

On the basis of in-situ measurements the Federal Ministry of Transport in the Federal Republic of Germany has published a directive for the shape of guide walls at single chamber locks (see Figure III-T).

Figure III-U shows a modern Dutch lock approach.

A diverging shape as drastic as possible is preferable for lock existing a symetrical shape with a slope of 1:8 is advised. The waiting area should be as close to the lock as possible with a guiding structure connecting the waiting area with the funnel shape guide wall preferred.

The minimum exit time is obtained with varying the shape and distance to the lock as shown in the figure. Any increase in distance will produce greater exit speeds but larger entry and exit times.

It should be remembered that European designs based on model studies involve European vessels with different dimensions and powering. Therefore, any recommendations would require verification by model testing in the United States. The guide walls can be concrete piles, floating concrete caissons, concrete slabs supported or sheet piles or simple pile structures with wooden walers. In particular, sheet pile structures have been found to be excellent for damping the kinetic energy of approaching vessels because they can withstand large deformations elastically. A highly rigid connecting beam at the top of sheet piles, driven at about five feet centers, ensures that forces are distributed evenly throughout the wall.

Model studies at Rijkswaterstaat in the Netherlands ("Navigation Locks for Push Tows," by Kooman[2]) have attempted to determine the optimum shape of guide walls

Figure III-T

(meters)
Lock Guide Walls (Recommended by the Federal Ministry of Transport in the FRG)

Figure III-U

A Modern Dutch Lock Approach

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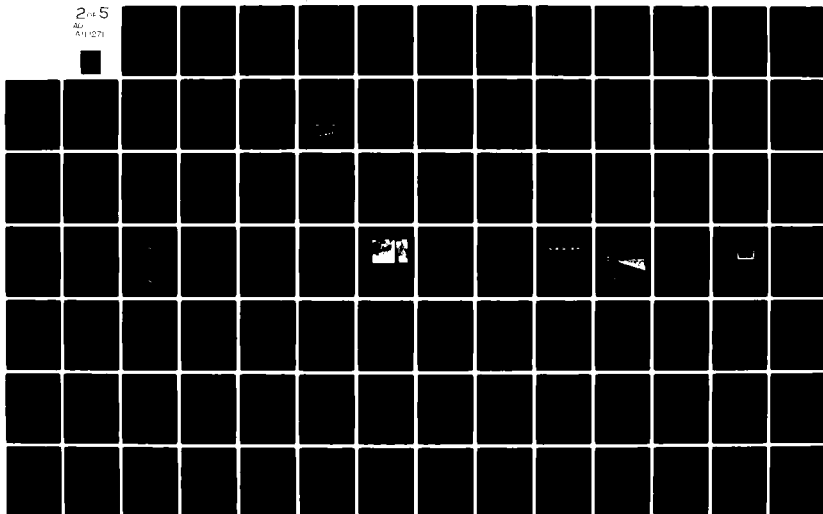
for European canals. Based on model tests, some of the conclusions for locks having two-way traffic are:

       1. a guiding structure without acute angles preferable to reduce the possibility of striking the lock wall.

       2. a funnel shape guide wall which is narrow near the lock entrance enforces optical guidance and reduces the risk of collisions; a symmetrical funnel shape is advisable with a slope of 1:16 near the lock and 1:6 in the wider portion.

Because of the much greater size and tonnage of United States tows, there is some doubt that funnel shape guide walls could be used in the United States as physical contact between the wall and the barge would increase the potential for damaging tows. At the present time, there is not sufficient documentation on the maneuverability of United States tows to determine the required dimensions of approaches similar to that shown in Figure III-U. Specifically, the distance required for a tow to become aligned with the lock entrance from the offset waiting area (where the tow is stopped) is not known.

In the Soviet Union the length of the guide wall for a one-way lock is selected in such a way that the entire tow (including not less than 0.6 times the length of the previous tow) may be berthed awaiting lockage. For two one-way locks at a site with approach channels and chambers having the same dimensions, the most common arrangement is fendered concrete piles between approach channels; if the chambers have different dimensions, then the two guide walls are built on opposite channel banks. Current practice in the Union of Soviet Socialist Republics has shown that locating guide walls continuous with and parallel to the lock wall is not an optimal solution. Entering a lock, a ship deflects to the opposite side; this leads to wearing of the lock wall when a vessel is being guided into the lock. For this reason, another design, that of displacing mooring walls 15-25 feet to the side of lock walls, is preferable. The entry conditions are improved; in addition, a waiting vessel may be brought closer to the lock gates, leading to some reduction in locking time. So far, this recommendation has only been verified for locks

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where the width is less than 60 feet. With one-way traffic at a chamber, the required length of the approach channel to allow entering vessel to maneuver into alignment with the lock is about 800 feet. The approach channel for exiting vessels need only be about 650 feet long. To account for vessels passing when exchanging the use of a lock for a two-way chamber, an allowance of 2700 to 2850 feet is provided for the length of the approach channel. Soviet vessels are usually limited to about 5000 metric tons and are required to be moored during a fly-exchange of a lock until the locking tow clears the moored tow. Although the approach distance appears to be very long (especially with the use of moorings), most Soviet locks are of the high lift type and have hydroelectric generating stations associated with them. This situation, in terms of hydraulic surges and currents is analogous to the system on the Columbia-Snake Waterway in the United States where approach distances are in excess of one mile.

(e) Safety Features

Safety devices that have been proven useful and effective at United States locks include: floating mooring bitts, improved radio communication systems, improved lighting for night operation, completely recessed ladders with safety belt rails for lock personnel, improved guard rails on the lock walls, electrical interlocks to prevent misoperation of lock gates and lock valves, and certain automated and programmed facilities to provide more consistent and reliable operation. Fail safe controls have been developed for locks where nonsynchronous valve operation produces hazardous lock chamber conditions. These devices will stop both filling valves if either valve lags the other by more than 0.5 feet. An electronic device was installed at Meldahl Locks to prevent overfilling and overemptying (this device may soon be installed on all Ohio River locks). Closed circuit television systems are also being provided to enable a lock and dam operator to view each side of the upstream and downstream gates, the approach channels and spillway sections of a dam. Improved audio warning signals, visual signal devices and public address systems have been developed to enable a lockman to advise tow operators or small craft operators of navigation conditions and issue warnings when necessary.

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One of the most important advances in providing safety
to tows and to tow personnel is the use of hydraulic
models to examine the approach conditions at a specific
site. This valuable tool enables designers to determine
the strength and direction of currents in lock approaches
and to develop layouts and approach channels that gener-
ally eliminate dangerous crosscurrents that would cause a
tow to founder on the dam and sink. Radio controlled
scale model tows are used in such river models and experi-
enced river pilots are consulted with regard to the per-
formance of the models and to the effects of improvement
measures. Such model studies have enabled designers to
avoid past mistakes on new projects, and lock approach
problems that are encountered at some of the older locks
do not occur at the projects built in the past 20 years.
Model studies have also been quite useful in studying
modifications to improve lock approaches at older
projects. These studies have resulted in such improve-
ments for safety as lengthened guide and guard walls,
location of mooring cells, location and design of sub-
merged dikes, and realignment of approach channels.

Hazards to small craft from the discharge outlets
exist at many locks with a lift of 20 feet or more and
where the outlets terminate in a single discharge basin
riverward of the river lock wall. During an emptying
operation flow from the basin wells upward creating a
large area of extreme turbulence that will capsize any
small craft over the outlet. Loss of life has been
experienced because of such turbulence at one of the new
Ohio River locks. Through model testing work, the
Tennessee Valley Authority developed a circular "stilling"
basin structure at Wheeler Lock that eliminates dangerous
turbulence. This type of structure was subsequently model
tested again by the Corps of Engineers and modified to
suit the physical and hydraulic conditions that exist
generally at the Ohio River locks. The structures work
satisfactorily at sites where variations in tailwater are
low. The structures also require excessively long
emptying culverts which tend to increase emptying times.
In almost all locations along the Ohio River the struc-
tures would have to be located downstream from the gated
spillway. This was not considered desirable.

Opponents also claimed that the structure could not be
made to be effective over a range of varying tailwater

elevations that would occur with varying river flow. The first argument against the structure had no sound basis and no valid reasons could be cited to support the claim that the location would adversely affect the spillway. The second line of objections were only partially valid. The model test (C. of E.) showed that the structure could be made to function satisfactorily from the normal lower pool stage through increasing stages up to a total lower pool rise of five feet. At such a time all of the spill-way gates would be at least 25% open and no small craft would be in the area. At the time the study was made (late 1960's) all of the 14 new Ohio River projects were either planned, designed or completed and the decision was made to give no further consideration to the structures. Two other safety devices that have been considered but have not generally been adopted in the United States are impact barriers and automated towing devices to move unpowered segments of a tow into or out of a lock.

Impact barriers, to prevent vessels from striking lock gates, are coming into wide usage in Europe, but have not been used in the United States except at the Soo locks and at the St. Lawrence Seaway locks. To date no completely satisfactory design has been developed that is suitable for tows having a sloping under surface on the bow end of the leading barge. However, the increasing frequency of accidents that damage lock gates is focusing attention on impact barriers and satisfactory designs should be developed. The use of impact barriers will undoubtedly in-crease the initial cost of some locks, especially if lengthening the lock chamber is necessary.

Towing mooring bitts, or traveling kevels as they are also known, have been studied for many years. Advantages from their use arise from faster operation with multiple lockage tows and possibly some lessening of hazard to lock personnel. However, there are also disadvantages. It has proven to be very difficult to develop designs that: pre-vent encroachment and interference to miter gate recesses; prevent obstruction to floating mooring bitts; do not adversely affect location and arrangement of guard rails on the lock wall; and finally development of enough trac-tive force to be effective. Some of the above problems can be minimized or overcome if towing mooring bitts are considered in the initial design and integrated with the other lock features. Nevertheless, many of the problems

have been overcome and towing mooring bitts have been suc-
cessfully installed at several locks on the Tennessee
River.

LOCKAGE TIME IN RELATION
  TO LOCK AND TOW
  CHARACTERISTICS

It is profitable for tow operators to utilize tows
which are as wide, as long, and having the greatest draft
as conditions will permit. When tows become too large,
however, so that clearances (between tow sides and lock
walls, guide walls and guard walls, between tow bow and
stern and lock gates, and between tow bottom and lock
floor, lock sill and approach channel bottom) become very
small, the speed at which the tow can approach, enter and
exit the lock is reduced. While tow operators have en-
crouched upon available lock width and length dimensions
to the point where as little as two feet of width clear-
ance and 10 feet of length clearance remains (supposedly
minimizing individual overall transit costs), to date, no
research has been performed in the United States to eval-
uate the effect of reduced clearances on lock service time
and navigation safety. Thus, no precise assessment can be
made of the effect of clearance on lock capacity based on
American research with tow sizes and lock sizes in use in
the United States.

The hydrodynamics of a tow entering a lock is roughly
analogous to a loose fitting piston in a cylinder. As the
head of the tow enters the confined space of the lock
chamber, more resistance is encountered because the water
in the lock chamber has to be pushed out underneath the
tow and along the side of the tow as the tow moves in.
Understandably, studies show that the entry time of a
given vessel (time required for a vessel to enter the lock
once it has become properly aligned), is related to the
area of the submerged cross section at the lock entrance.

To improve entry times, then, additional chamber
cross-sectional area is required. On most filling
systems, especially side port systems, proper design and
functioning of a lock's filling system is contingent on
the depth in the lock chamber. This required lock chamber
depth is almost always greater than the available channel

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depth by a substantial amount. Thus, the draft that tows
can be loaded to is fixed by channel depth and since the
lock chamber depth has to be substantially greater then
the vessel draft, there remains only the question of the
proper elevation for the lock sills. By placing the top
of the lock sills only two feet (or so) higher than the
lock floor, the gate height and cost is increased, but the
amount of concrete required for the sill and its cost is
reduced. The net result is that an increase in gate cost
is offset by a saving in sill cost for low to medium lift
locks with adequate submergence. Hence, additional cross-
sectional clearance space is obtained, at no increase in
cost, which tow operators cannot encrouch on because of
channel depth limitations.

Recognizing the potential time savings in this area
and the potential for increasing the capacity of existing
lock facilities, a proposal was submitted several years
ago by the Waterways Experiment Station of the Army Corps
of Engineers to study the effect of submergence, vessel
drafts and forces on vessels in order to optimize the
depth over sill (differences in elevation between normal
pool and gate sill) of United States locks. The study is
tentatively scheduled for funding in fiscal year 1982.

Currently, the Army Corps of Engineers recommends (ETL
11102-223, dated June 1977[3]) a depth over the lower sill
of at least two times the vessel draft when the lock
chamber depth is greater than two times the vessel draft
plus three feet. When the lock chamber depth is less than
two times the vessel draft plus three feet, the lower gate
sill of from zero to three feet is recommended. The upper
sill depth according to the ETL should be at least equal
to the lower gate sill depth but greater upper sill depths
could be advisable if special operating conditions such as
hinged pool operation and provisions for navigation of
special equipment in case of loss of pool are considered.
Additional depth over sill may be necessary if signi-
ficant ice accumulations on the bottom of vessels is
anticipated.

The recommendations of the ETL are based on model
tests performed in Europe where it was found that
efficient entry times were obtained when the sill depth
was 1.8 to 2.0 times the vessel draft. The following

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paragraphs discuss some aspects of European experience in this area.

For a given vessel which has a known draft (either laden or unladen) and a known horsepower, it is possible to relate the blockage ratio (the area of the largest cross-section of the vessel divided by the area of the wet cross-section at the entrance) to the entry time. The relationships have been developed for standard European self-propelled vessels and are provided in Figure III-V. The curves were prepared based on observations at 21 European locks with a total of 30 chambers and presented in the publication "Lock Capacity and Traffic Resistance of Locks" by Kooman. The standard vessel sizes for which the figure was prepared are shown in Table III-1.

It can be seen that the entry and exit times increase rapidly with increasing blockage ratios for the larger vessels.

Table III-1

Classification of Deadweight Tonnage Categories of Standard European Vessels

No.	Deadweight Tonnage Category (metric tons)	Standard Vessel Data			
		Deadweight Tonnage (metric tons)	Length (m)	Beam (m)	Draught (m)
0	50 - 199	125	25	4.6	1.6
1	200 - 449	325	39	5.1	2.3
2	450 - 749	550	50	6.6	2.5
3	750 - 1149	925	67	8.2	2.5
4	1150 - 1549	1350	80	9.5	2.6
5	1550 - 2549	2000	95	11.5	2.7
6	2550 - 4999	4100	175	11.4	3.0
7	>5000	8800	185	22.8	3.2

While the relationships derived do not depend on the size of the lock, it is not possible to directly extrapolate the results for different vessel sizes.

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Figure III-V

Entry and Exit Intervals of Laden and Unladen Standard Self-Propelled European Vessels
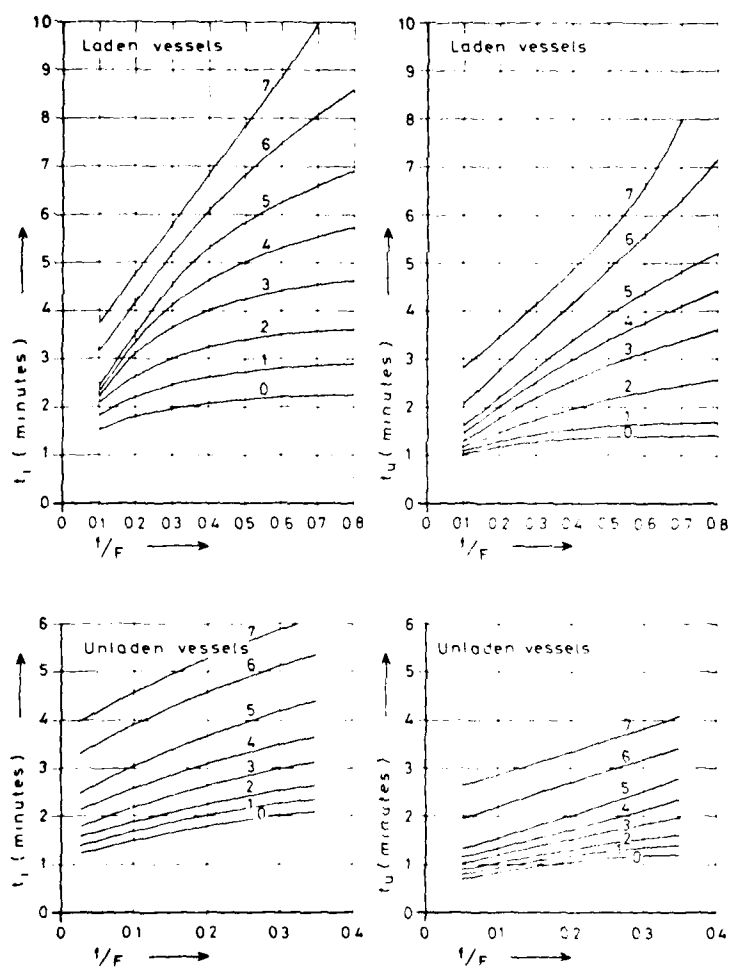
f/F = Blockage Ratio
ti = entry
tu = exit

Model tests to determine the time of entry for tows were also performed and published in the report "Navigation Locks for Push Tows"" by Kooman. The model tests were conducted for two types of tows having the dimensions: 191 m x 22.8 m x 3.3 m (626.5'x 74.8'x10.8') and 178 m x 19 m x 3.2 m (583.8'x62.3'x10.5'). Figure III-W was prepared from the results of the tests. The duration of the entry was measured from the moment the bow crossed the sill until the stern of the towboat had entered 25 meters (82 feet) into the lock. The propeller speed was kept constant during the tests except for one test (as indicated on Figure III-W where the initial speed was 1.0 m/s and the speed of the propeller increased when increased resistance was felt. As a result of that test, the entry time was identical to that at a constant speed of 2 m/s. The height of the sill was 1.25 m (4.1 feet) plotted in Figure III-W. The depth of water over the lock floor (h) was varied. The depth over the sill in each test was therefore h minus 1.25 m. Table III-2 shows the duration of the entry obtained by varying the height of the sill (D) with respect to the depth of water over the lock floor (h).

Figure III-W

Duration of Lock Entry

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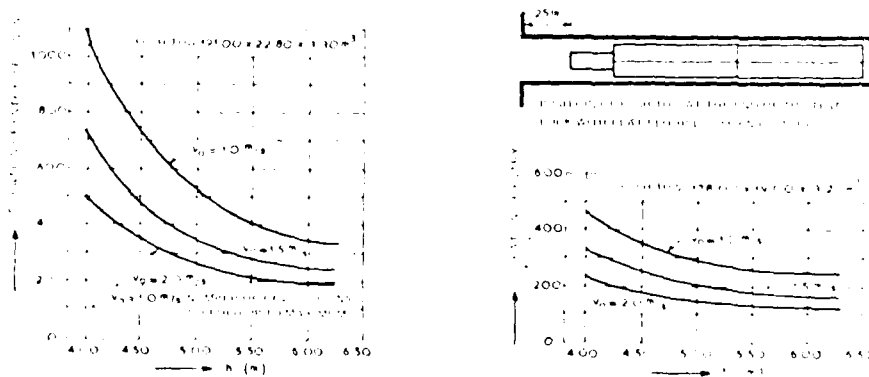
Table III-2

Duration of Entry for a Lock With or Without Sills at Constant Propeller Speed

Push tow	h (m)	V_0 (m/s)	Duration of Entry (min.) for:		
			D=0m	D=0.50m	D=1.25m
191 x 22.80 x 3.30m³	4.50	1.5	8.0	9.6	~
191 x 22.80 x 3.30m³	5.00	1.5	5.7	–	~
191 x 22.80 x 3.30m³	5.50	1.5	4.6	4.9	6.6
191 x 22.80 x 3.30m³	6.25	1.5	4.0	–	5.7

The investigation concluded that the duration of entry is not dependent upon the length of the lock, provided, of course, that at least 25 m (82 feet) of clearance between the stern of the lock and the towboat is available (with additional clearance in front of the bow).

Similar analytical relationships were developed for the duration of exit as shown on Figure III-X. Again, the starting point was 25 m (82 feet) from the lock sill and measurements were continued until the stern of the towboat cleared the sill.

Figure III-X

Exit Times at Various Waterdepths and Numbers of Revolutions

104
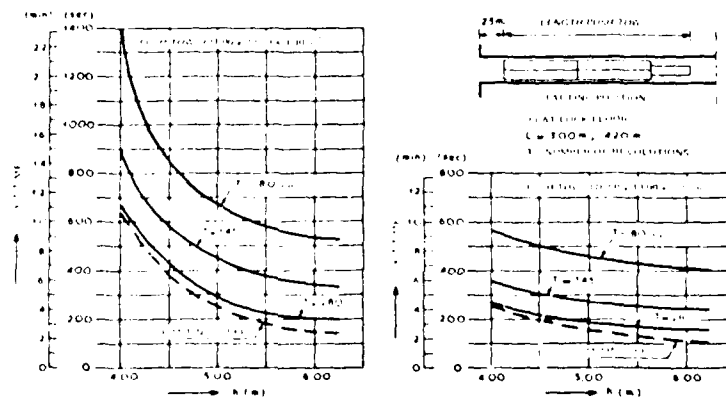
Similar research in the Union of Soviet Socialist
Republics has allowed relationships between tow size,
chamber size and entry time to be developed. These
relationships are shown in Figure III-Y (from Kir'yakov,
et. al., "Allowable Ship Speed in Locks"[5]).

In England, tests have been performed for ships
drawing about 35 feet and having blockage ratios greater
than 85%. The relationships obtained are shown in Figure
III-Z. It should be noted, however, that it is not suffi-
cient to relate entry time to the blockage factor alone as
variations in depths influence entry hydrodynamics much
more than variations in widths.

WATER SAVING STRUCTURES

In some instances it may be desirable to install a
navigation structure where adequate water may not be
available to allow regular cycling of a lock, particularly
at light levels of utilization. Alternatively it may be
more profitable to reserve impounded water for hydroelec-
tric power generation. In these cases, in lieu of using
shiplifts it may be more economical to construct water
savings basins (thrift basins) accompanying the locks.
Saving basins are currently being considered for use on
the Coosa River where locks are planned with lifts up to
130 feet. The use of savings basins on the Coosa River
would permit lockages without diverting a significant
amount of water away from existing hydroplants on the
river.

The purpose of water saving basins is to store a
portion of the water used during the lockage emptying
cycle to be reused during the filling cycle. This can be
accomplished by gravity flow into storage reservoirs.
Figure III-AA obtained for the Leerstetten Lock on the
Main-Danube Canal, shows the relationship between the per-
centage of water which can be saved per lockage cycle to
the ratio of the area of the water saving basins to the
area of the lock chamber as a function of n, the number of
water saving basins.

It is obvious that only a negligible saving in water
is gained when m 1. A total balancing of the water

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Figure III-Y

Nomogram for Determining Water Depth in a Lock Chamber
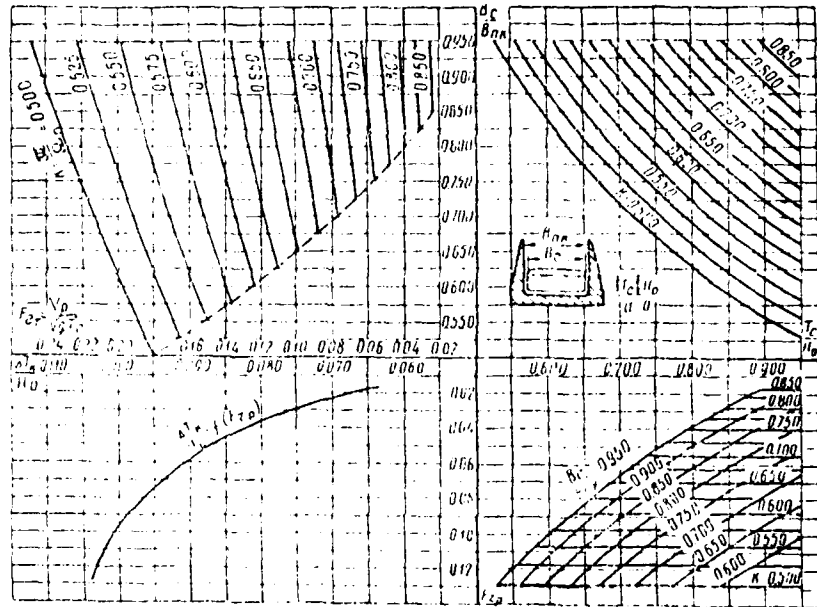
H_O = water depth in chamber

B_{nk} = chamber width

ΔT_k = vessel squat

T_c = vessel draft

B_c = vessel width

V_p = vessel speed

F = Froud Number

K = blockage factor = $\dfrac{T_c B_c}{H_o B_{nk}}$

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Figure III-Z

Lock Entry Times Using Towing and Propeller Forces

A = BOW TUG + DEAD SLOW AHEAD ENGINE
B = BOW TUG + SLOW AHEAD ENGINE

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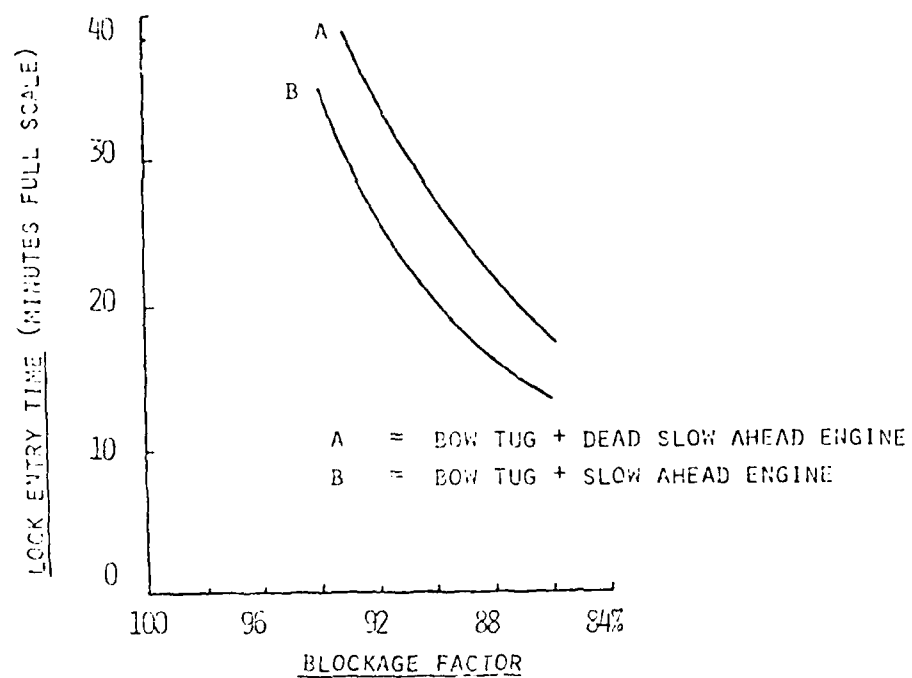
Figure III-AA

Water Saving vs. the Ratio of Lock Chamber to Saving Basin Area for Various Numbers of Basin

Leerstetten: $H_0 = 25m$, $a = 0.15m$, $m = 1$, $n = 3$
total lockage water: $61400 m^3$; saving water $36200 m^3$; lost water $25200 m^3$

% of water saved

$E = 59\%$

$$m = \frac{\text{area of the water saving basin}}{\text{lock chamber area}}$$

n = number of basins
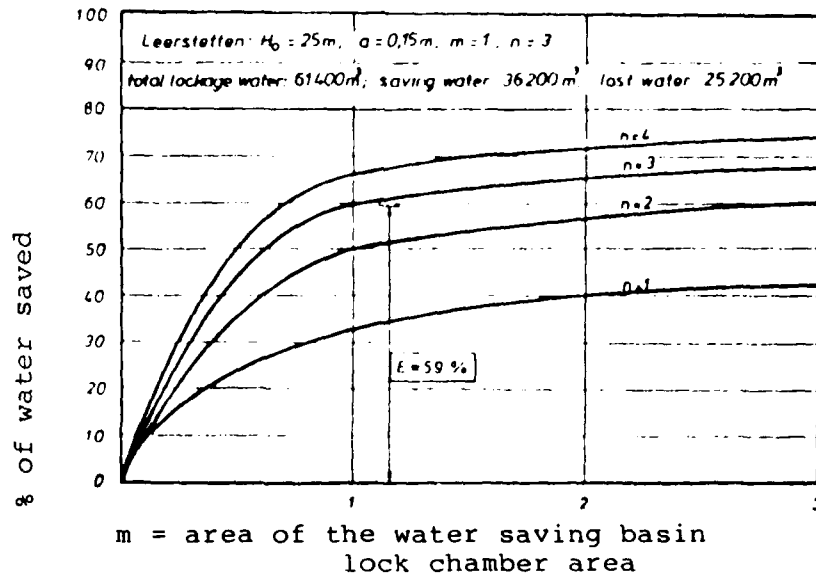
SOURCE: Brokonsult, Study of the Navigable Waterway Between the Danube and the Aegean Sea.

levels in the saving basins and the chamber does not result in a significant water saving, but in a remarkable prolongation of the lockage time. By increasing the number of saving basins above n 3, additional water cannot be saved economically.

Experience and analysis from the Main-Danube Canal resulted in the conclusion that locks with a total head between 55 and 85 feet, in general, are most economical if they are equipped with three basins having the same area as the lock number. Figure III-Z for example, shows that for the Leerstetten Lock, with a lift of 82 feet, the water savings is about 59%.

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In the Theodor-Rehbock-Laboratory for River Improvment at the University of Karlsruhe (FRG), a special filling and emptying system for locks with saving basins for the Main Danube Canal (MDC) was developed by model investigations. It is a combined system of longitudinal culverts in the lock chamber walls connected with energy dissipation chambers below the lock floor and vertical ports in the lock chamber floor. This system has been applied at most of the MDC locks. As an example, Figure III-BB shows a plan and a longitudinal and cross section of the Eckersmuhlen Lock (lift: 82 feet).

Experience operating locks with saving basins on the MDC were so satisfying that the Uelzen Lock on the Elbe-Lateral Canal (ELC) with a lift of 75 feet, was also built with saving basins and a similar hydraulic system (see Figure III-CC).

The average raising velocity of the water level in the chamber of the Eckersmuhlen Lock is 1.6 m/min., the maximum velocity is 3.35 m/min. The maximum hawser forces during a normal filling operation are about 0.5 tons on a so called "European vessel." i.e., a self-propelled vessel with a capacity of 1350 tons, a length of 263 feet, a width of 31.2 feet, and a draft of 8.2 feet.

The flow distribution and the water surface during lock operation are so smooth that vessels in these types of locks do not have to be moored during lockage. On the basis of investigations at the Theodor-Rehbock Laboratory and experience with the operating prototypes, it can be assumed that this type of lock can be operated satisfactorily and without endangering vessels, even with heads exceeding 82 feet. (Model investigations for a 125 foot lift lock with water saving basins have already been executed in the Bundesanstalt fur Wasserbau in the Federal Republic of Germany.) Further water savings can be achieved by pumping back lockage water to the upper approaches.

The Hydraulic Constructions Laboratory of the University of Liege (Belgium) has been studying new ways of constructing high-lift locks for many years. These studies have clearly shown that in Belgium there are advantages of

Figure III-BB
Lock Eckersmuhlen

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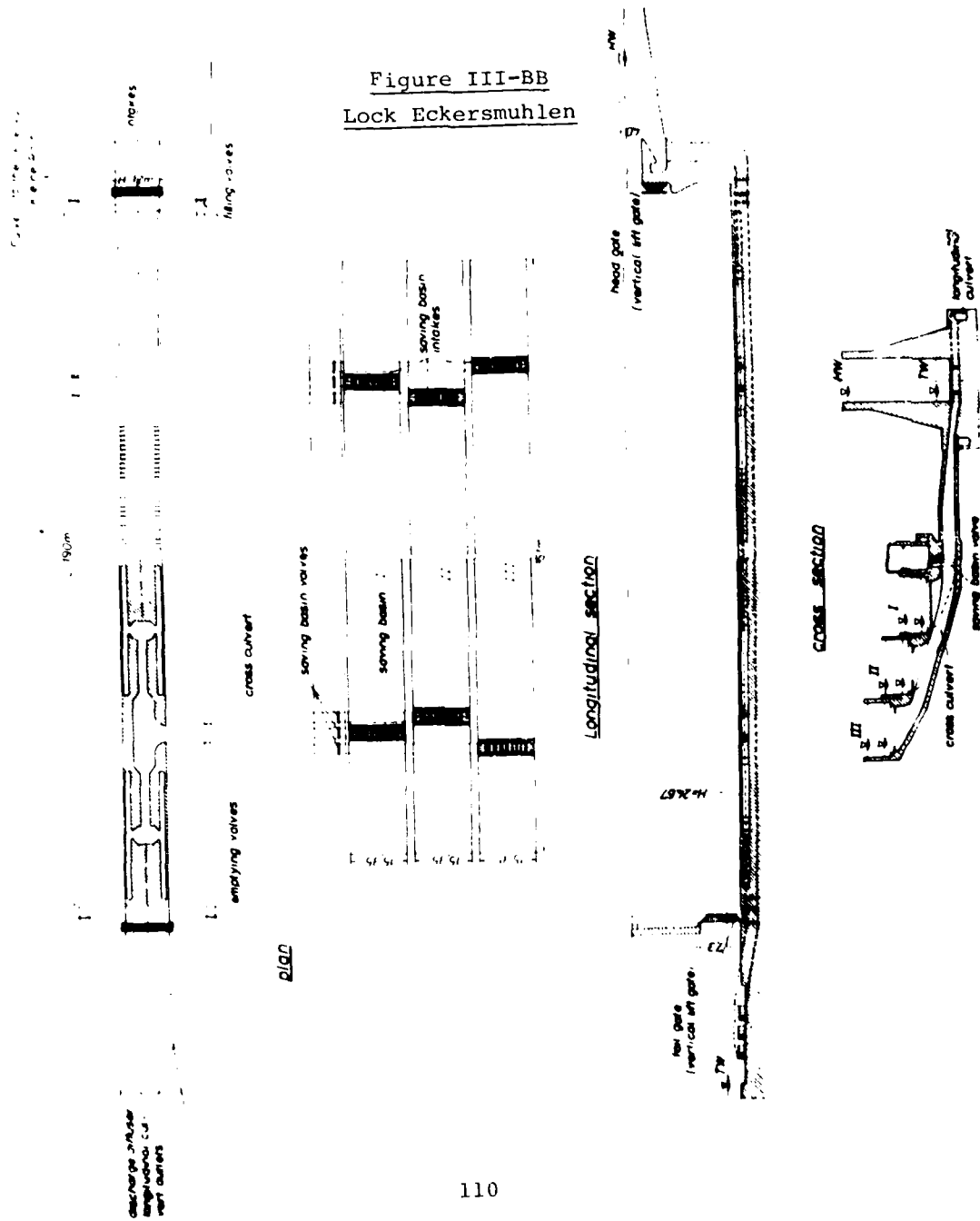
Figure III-CC

Example of a High-Lift Lock with Water
Savings Basins

Lock Uelzen
Elbe-Lateral-Canal

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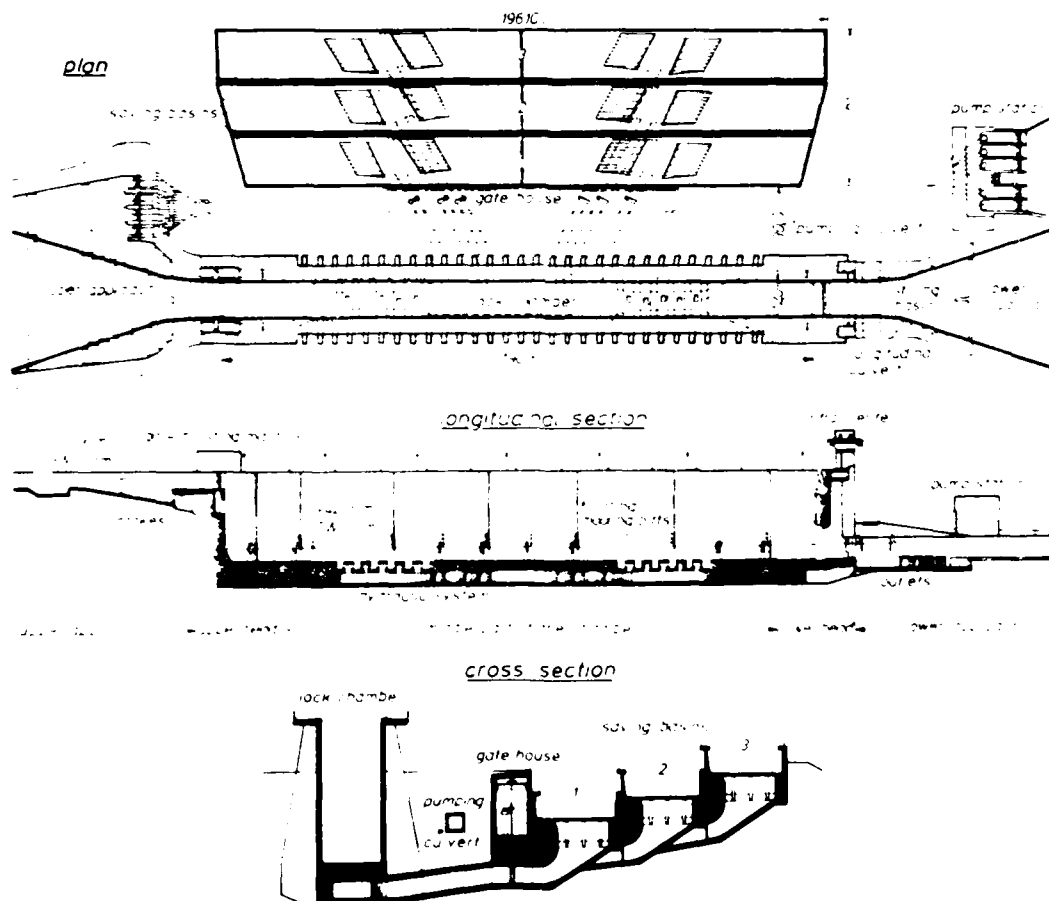
incorporating saving basins into the lock walls during construction of very highlift locks (160 to 200 feet). This practice allows the reduction of both excavation and concrete volumes. Furthermore, their theoretical studies show that utilization of saving basins makes it possible to lock a 160 foot lift in 21 minutes, the mean rising velocity being 0.04 m/s. During filling, currents have a minimum velocity of 0.066 m/s at half-depth of the chamber, but they are limited to 0.03 m/s at the highest and lowest levels, where water is exchanged between the lock and the navigational channel. The new design, developed for these special very high-lift locks indicate that cavitation may be reduced without excessive complications. Finally, it should be pointed out that this new type of lock structure is extremely rigid and resistant without excessive use of concrete. This characteristic is very interesting for applications in seismic regions.

SHIPLIFTS

In the United States and in Europe, locks have been constructed with lifts in excess of 100 feet (Ice Harbor, Lower Monumental Lower Granite, and John Day Locks with lifts slightly in excess of 100 feet on the Columbia-Snake Waterway; Carrapatelo Lock or the Douro River in Portugal with a lift of 113 feet; Ust-Kamenogorsk Lock on the Irtysh River in the Union of Soviet Socialists Republic with a lift of 138 feet). In general, whenever lifts have exceeded about 65 feet, Europeans, in many cases, have found it more advantageous to construct shiplifts instead of high-lift locks for vessels with a cargo capacity of 1350-1500 tons. This has been borne out, in particular, by studies made in the Federal Republic of Germany in the course of designing navigation structures on the canal connecting the Mittleland-Kanal with the lower reaches of the Elbe River. According to studies made in the USSR, the installation of shiplifts becomes, in general, more economical than locks for vessels designed for a cargo carrying capacity of 5000 tons, beginning with lifts of 165 to 200 feet. This limit is evidently in the neighborhood of 130 feet with 2000-3000 ton vessels.

Figure III-DD taken from the paper, "The Outlook for the Development of Water Transportation - Waterways and Waterway Management" by Hochstein shows the relative percentage of projects on which shiplifts have been used or

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proposed in lieu of locks, for various heads in the Union of Soviet Socialist Republics. The data was plotted using mean data for vessels having a capacity between 3900 and 5000 tons.

Figure III-DD

Use of Shiplifts vs. Locks in the
Union of Soviet Socialist Republics
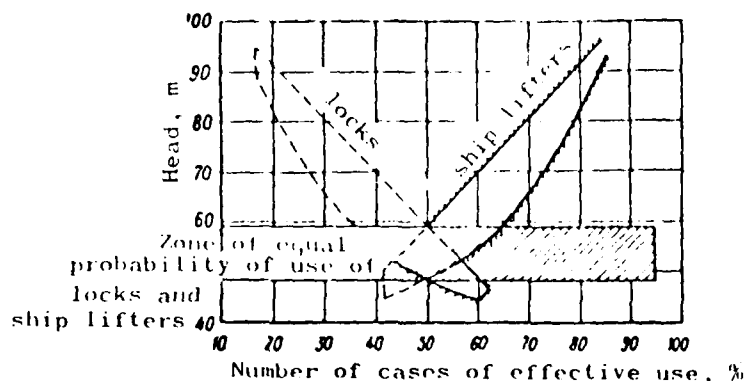
SOURCE: "The Outlook for the Development of Water Transportation, Waterways, and Waterway Management," Hochstein, 1973.

When lifts become very great, locks require long lockage times and great water consumption. Several types of shiplifts are currently in use including hydraulic shiplifts, floating shiplifts, cable shiplifts, longitudinal inclined planes, traversal inclined planes and water slopes. Up to now, no shiplifts have been constructed with a length exceeding 330 feet, so that tows must break before using them. Due to the very small size of the shiplifts, which would only be capable of accommodating one or two United States barges, it is very unlikely that the use of such shiplifts could ever be justified in the United States. However, the widespread use of shiplift structures and their history of reliable operation attest to the soundness of the technology. Shiplifts are not so dependent on the height of the lift. Shiplifts utilize moving containers, which have gates at both ends to open into the upstream and downstream reaches allowing vessels to enter or leave the containers. When the gates are

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closed, the container can lift or lower vessels from one reach to the other, either vertically or on an inclined plane.

The theoretical advantages of movable container structures are:

1. Negligible water-consumption.

2. The possibility of attaining very high lifts.

3. Above a certain lift, the vessel service time is less than in a series of locks, however, the capacity is much less.

4. A comparatively lower cost than locks, above a certain lift.

5. The vessels are floating during the passage and thus the weight of the container is constant.

The drawbacks of this kind of structure are:

1. The very high weight of the moving elements (two to three times that of the vessel).

2. The mobility of the water-mass inside the container, which poses a dangerous condition for the mooring of vessels and the stability of the container. Consequently, inclined planes must move slowly, and in shiplifts lateral effects (surges, poor guiding, earthquakes, wind forces) must be avoided because of the great inertia of the contained water-mass.

3. The difficulty of maintaining a watertight seal between the moving container and the navigation canal (the water pushing against the opposite closed gate of the container tends to open the joint.

4. Mechanical equipment is always more difficult and expensive to operate and to maintain than in a lock.

5. The relatively low capacity of existing ship lifts.

The various types of shiplifts, their advantages, disadvantages and range of applicability will be discussed briefly for each type below.

(a) Hydraulic
     Shiplift

Hydraulic shiplifts consist of two containers placed side by side. They are lifted by huge pistons and cylinders (Figure III-EE).

The cylinders are interconnected by a hydraulic conduit closed by a main valve. The weight of both containers is equilibrated by the pressure of the liquid. The lowering of one of the containers is achieved by the release of 8 to 12 inches of water from the other, lower container.

Hydraulic shiplifts have been working satisfactorily in France, Belgium and Canada. They are rugged and quite dependable once they are adjusted. Their main drawbacks are the interdependence of the containers and the danger of the breakdown of the hydraulic system. The primary features of hydraulic shiplifts are as follows:

- low water consumption.

- moderate lifting speeds (0.04 m/s).

- capacity limited to 350 ton vessels.

- lift limited to 65 feet.

- the high rigidity of the structure.

No new hydraulic shiplift has been built since the turn of the century although the hydraulic lift at Peterborough, Ontario, was rehabilitated in 1963.

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Figure III-EE

Hydraulic Shiplift, at Peterborough, Ontario*
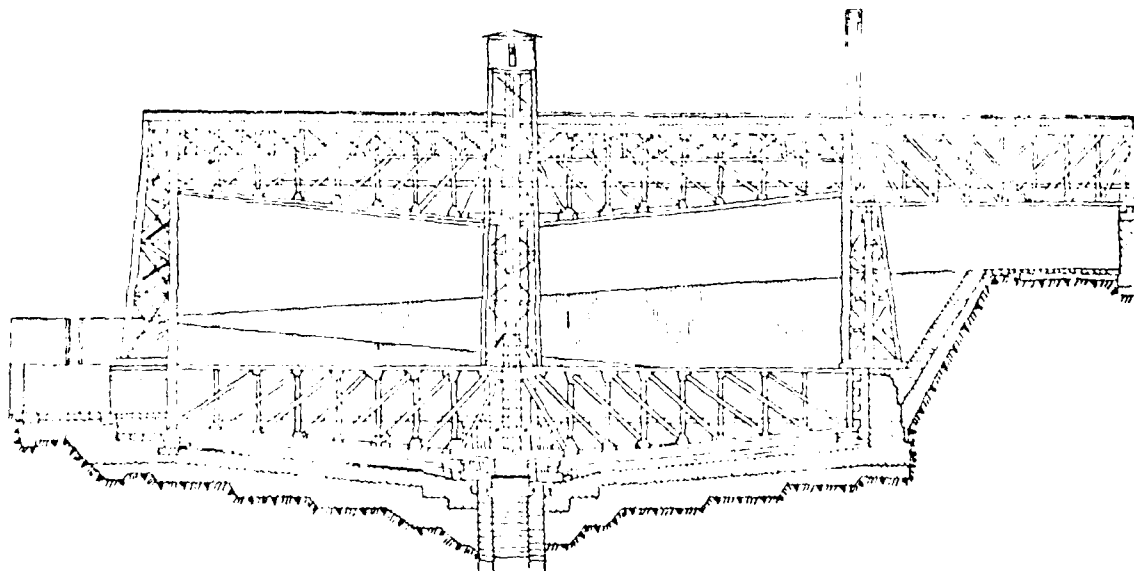
*Constructed 1904, updated 1963
 Lift - 65 Feet
 Chambering Time - 10 Minutes
 Chamber Size - 139'x33'x61'
 Capacity - 1500 Tons

(b) Floating
     Shiplifts

The container of a floating shiplift is supported by
floats. The float wells must be deep so that they can be
connected to the downstream reach. This is the major
drawback of this type of shiplift. The container is
guided vertically between towers and lifted by worm screws
fixed to the towers.

Because of friction, in spite of the floats, motive
power is necessary to lift or to lower the container.

The ancient shiplift of Henrichenburg has five floats
(Figure III-FF). Up to one million ship passages have
been accomplished without serious problems.

The hydrostatic pressure on the floats and the re-
sulting stresses become greater as the vertical rise in-
creases. The same goes for the length of the worm screws,
which are relatively fragile mechanisms. But these appear
to be the only considerations limiting the vertical lift
that a floating shiplift can overcome.

In order to do away with float wells, or at least to
limit their depth, German engineers have designed ship-
lifts with lateral floats. However, such a shiplift has
not yet been built.

(c) Cable Shiplifts

In cable shiplifts, either two containers are sus-
pended by chains or cables passing over pulleys and bal-
ancing each other, or, preferably, one container can be
balanced by counterweights.

The whole structure is above ground. There are no ex-
ceptional or delicate elements, so that the device is an
economical one. The erection, adjustment and operation of
a cable shiplift is easier than that of a hydraulic ship-
lift. At rest, no displacements can take place, unlike
with a leaking hydraulic piston.

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Figure III-FF

Ancient Shiplift of Henrichenburg

118
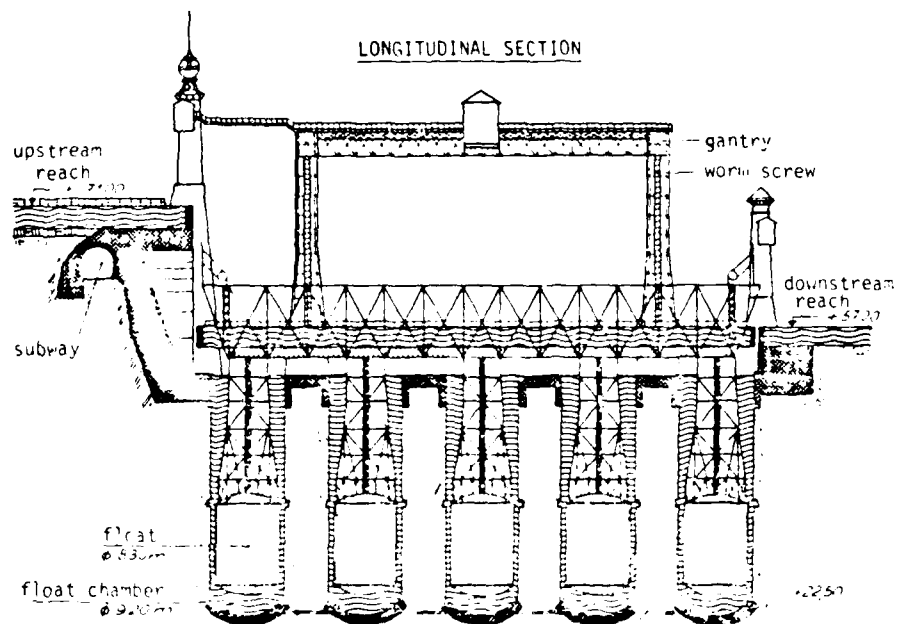
The first big cable shiplift was that of Niederfinow (East Germany) built in 1934. It has a single container 280 feet long and 40 feet wide, lifting 1000 ton vessels. With a 118 foot lift it was for many years the largest of its kind.

The Luneburg Shiplift build in 1976 on the Elbe Lateral Canal passes 1350 ton vessels in two independent containers 328 feet by 40 feet. The lift is 125 feet. (Figures III-GG and III-HH.) In addition, the construction of a double 1350 ton cable shiplift will soon start in Belgium at Strepy-Bracquegnies on the so called "Canal du Centre." This shiplift will have a lift of 250 feet.

(d)   Inclined Planes

With inclined planes the vessels are, like in a shiplift, transported floating in a container, but traveling on an incline.

If the container travels lengthwise, being towed or self-propelled, it is called a *longitudinal inclined plane* (Figure III-II) If, on the contrary, the container is towed sideways, it is called a transversal inclined plane (Figure III-JJ).

Inclined planes usually follow the natural ground slope. Their electromechanical equipment is complicated and expensive. The main difficulty in their construction results from the enormous moving load (vessel + container + water + running gear = almost four times the weight of the vessel) and requiring a very stable and continuous supporting structure.

The surge of water inside the container can lead to excessive mooring forces; consequently, the traveling speed and particularly the acceleration must be very low.

The best example of a towed longitudinal inclined plane is that of Ronquieres in Belgium (Figure III-KK).

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Figure III-GG

The Luneburg Cable Shiplift

LONGITUDINAL SECTION AA
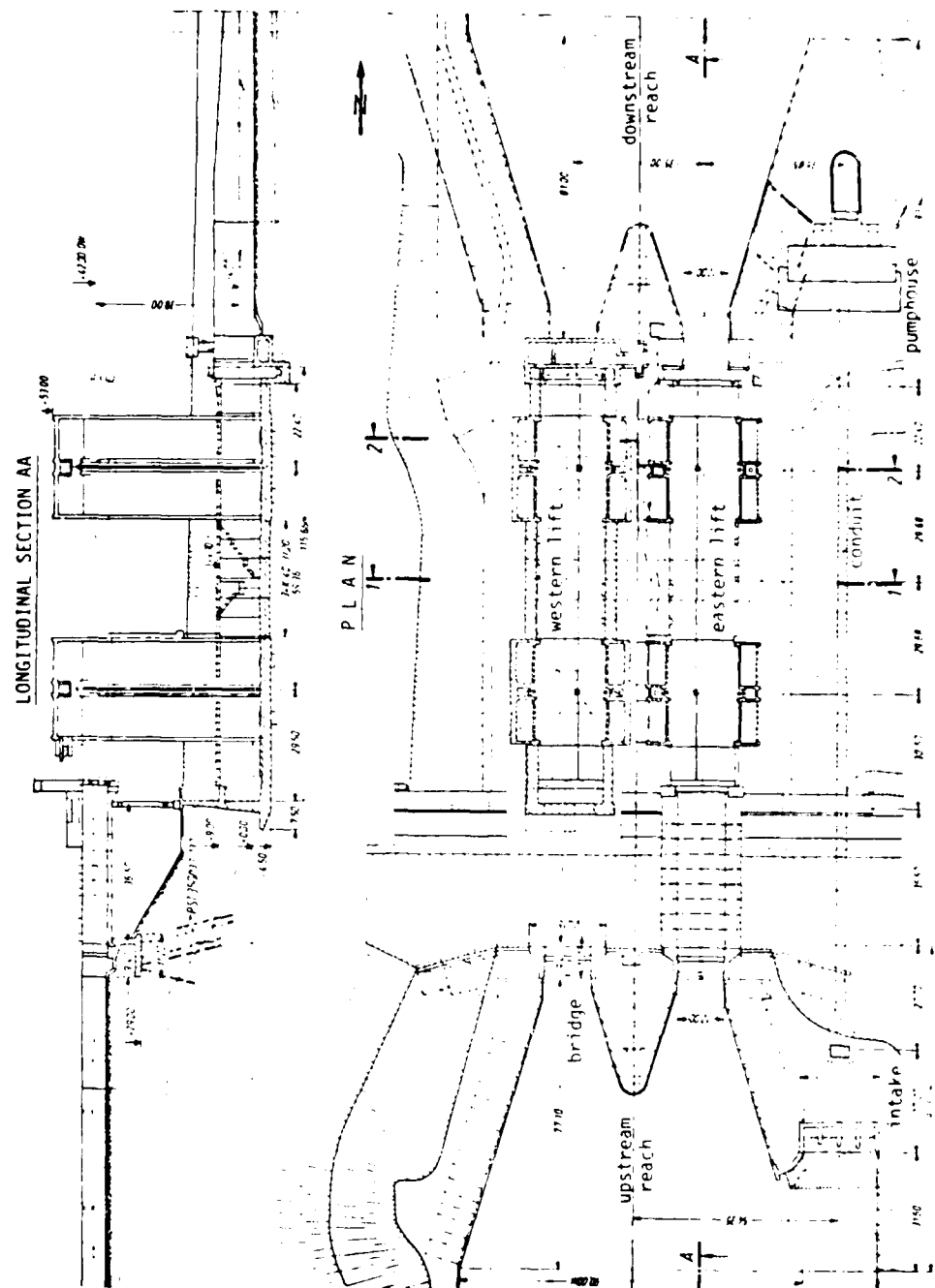
PLAN

Figure III-HH

The Luneburg Cable Shiplift
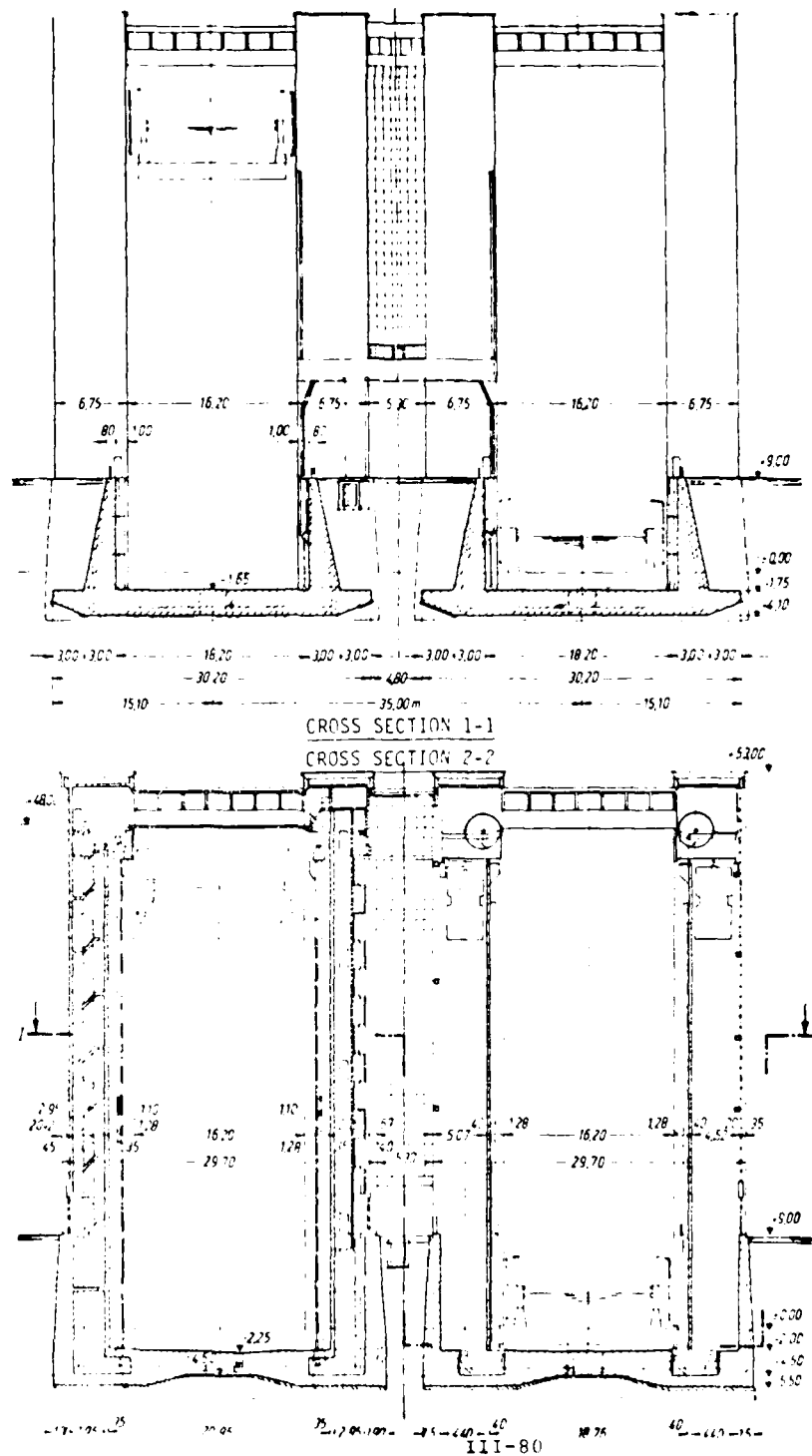
Figure III-II

Longitudinal Inclined Plane
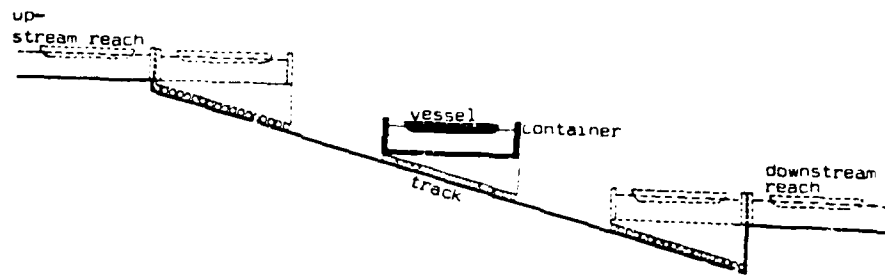
Figure III-JJ

Transversal Inclined Plane
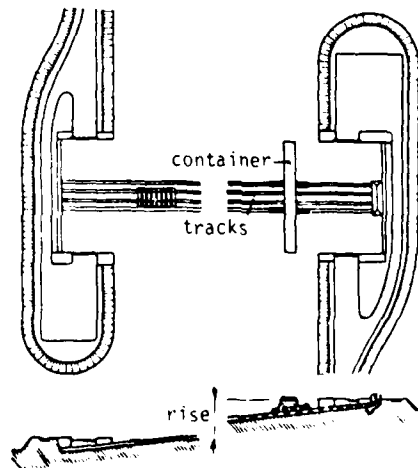
Figure III-KK

Ronquieres Inclined Plane

ELEVATION

elevated
canal | container 1 | | | | container 2

driving gear | counterweight 2 | | | | counterweight 1

PLAN

container 1 | | | counterweight 1

counterweight 2 | | | container 2

CROSS SECTION AA | CROSS SECTION B
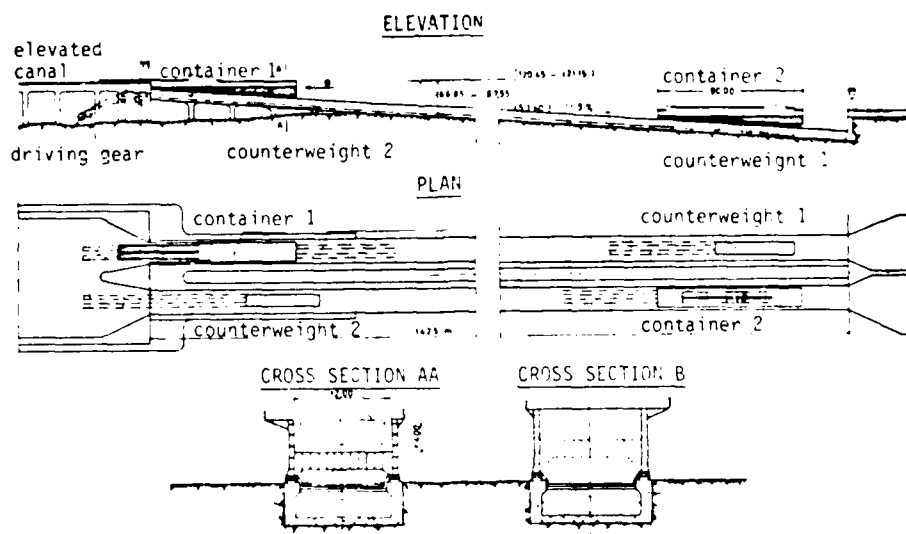
The Ronquieres Inclined Plane has two independent containers, each one being connected to its own concrete counterweight by eight cables. The containers are 300 feet long between gates and 40 feet wide. The gates are protected by fenders, so the useful length is only 285 feet, similar to that of a lock for 1350 ton vessels.

The water-depth in the container is 10 to 12 feet depending on the water-level in the upstream and downstream canals. Local conditions led to the adoption of a 5% slope ramp.

The total mass of a complete container full of water is between 5000 tons and 5700 tons and rests elastically on two rows of 59 two-roller axles.

The studies during the design showed that an instantaneous uniform 1 cm/s^2 acceleration of the container would result in a mooring strain of 25 kN to 30 kN for a 1350 ton vessel. This could be acceptable though it is more than the traditional value of 1/1000th of the vessel displacement.

These mooring strains can be reduced to only 3 kN to 4 kN if the acceleration is gradual from 0 to 1 cm/s^2 in 35 seconds.

A one-way movement of the container takes 22 minutes. With two-way navigation a complete cycle lasts 50 minutes, and with one-way traffic 40 minutes. This is very similar to the time required for a conventional lockage, but would have only about 20 to 25% of the capacity of a lock system.

With a self propelled inclined plane the driving gear is carried on the container, thus the transport length and consequently the lift is not limited by the length of the cables.

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In addition, this system allows great variations in water levels both upstream and downstream (13 m upstream and 6.50 downstream at Krasnoyarsk).

The only large self-propelled inclined plane is employed at Krasnoyarsk (USSR) on the Yenisey River, with a lift of 330 feet (Figure III-LL).

The inclined plane has two 10% ramps with a turntable in between. The lower ramp is 4070 feet long and the upper one is 1640 feet long. With the direction of the travel being changed at the turntable, the container must be self-propelled.

The container has a usable length of 295 feet, a width of 60 feet and a mean water depth of 7.2 feet being able to pass 1500 to 2000 ton vessels.

The vessels enter and leave the container at the same end, equipped with a segment-gate. At the other end are located the control room and part of the driving machinery. The rest of the machinery is located alongside the container (Figure III-MM).

The overall container length is 355 feet, and the overall width is 87 feet. The total weight with water is 6720 tons.

The container ascends at a speed of 3.3 feet/s and descends at 4.4 feet/s. The acceleration is limited to 8 mm/s^2. The complete cycle takes about 90 minutes.

The capacity of this inclined plane is lower than that of similar sized locks, but it is possible to put a second container in service, the crossing being made at the turntable with one of the containers on a siding.

The container of a transversal inclined plane travels sideways and has counterweights (Figure III-NN).

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Figure III-LL

Krasnoyarsk Inclined Plane, General Layout
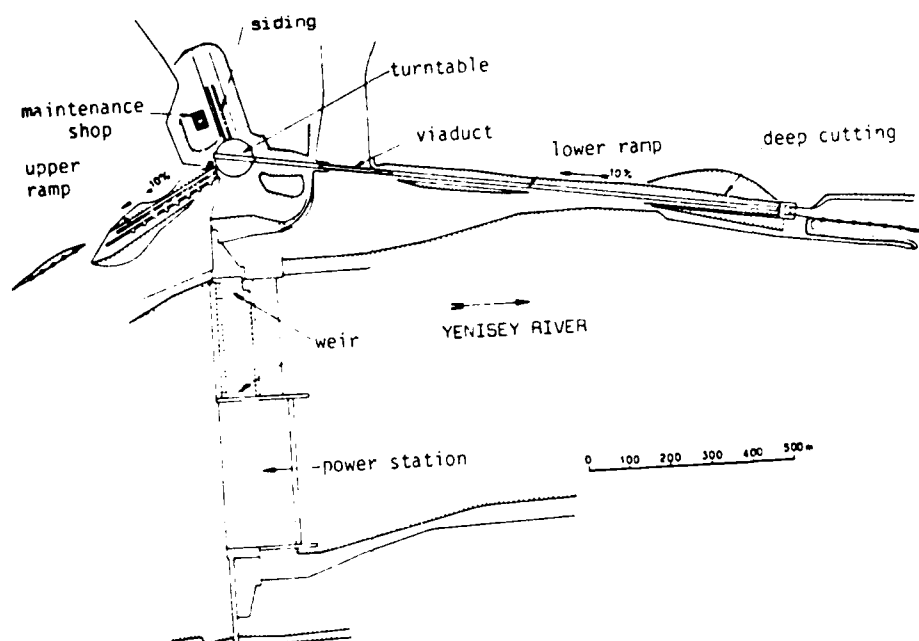
Figure III-MM

Krasnoyarsk Inclined Plane, Self-Propelled Container
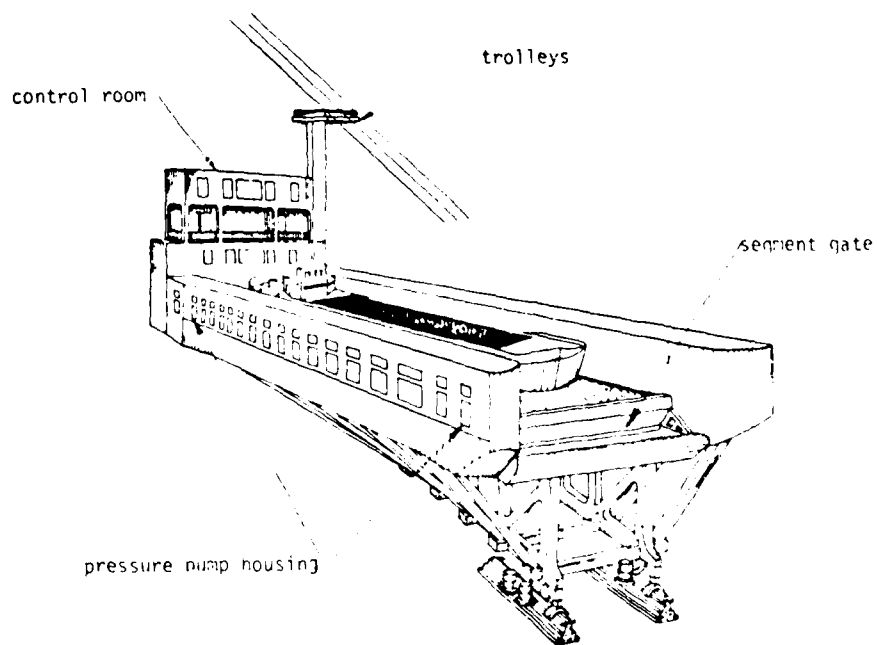
Figure III-NN

Transversal Inclined Plane
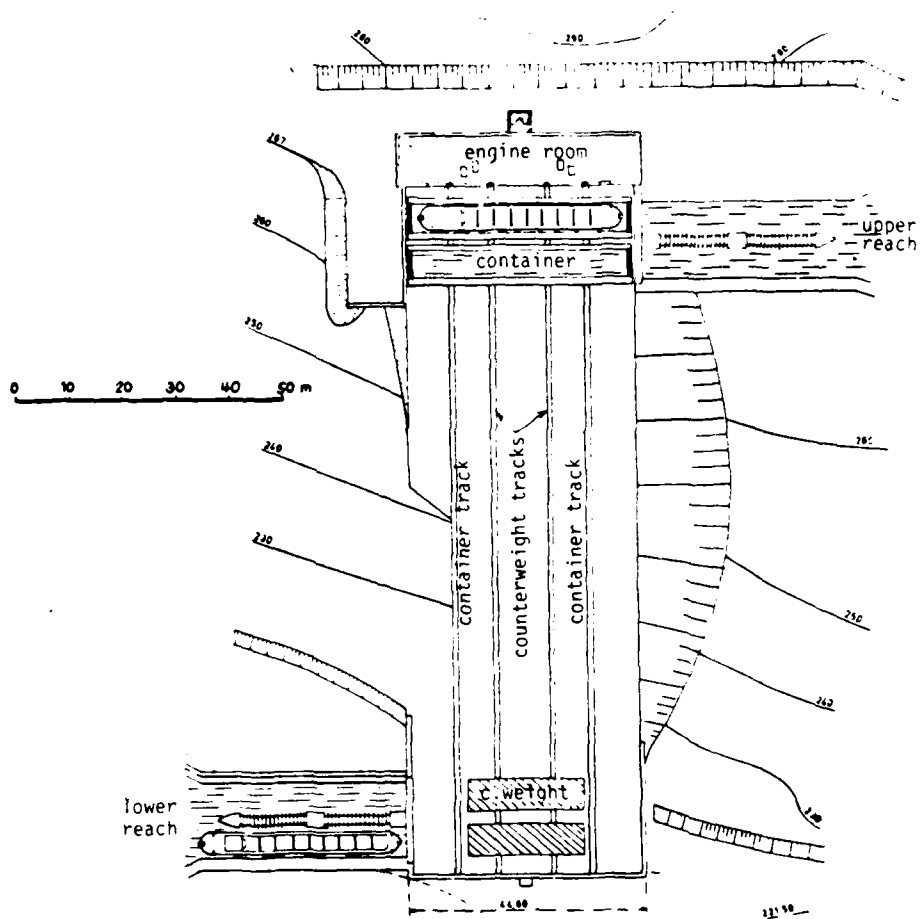
With the same size container, the transversal inclined plane has certain advantages over the longitudinal type:

1. Serious water surges are less likely to develop in the container because the water surface is shorter in the direction of travel.

2. The slope can be much steeper without having to support one end of the container on high steel structure. A steep slope results in a shorter inclined plane. This is a very important economical consideration, because the ramp of a transversal inclined plane is very wide, its width being close to the length of the container.

3. The necessity of a steep slope practically excludes self-propelling containers in transversal inclined planes.

There are of course drawbacks:

1. With a steep slope the strain on the driving pulleys is much higher.

2. The guidance of the container is more difficult because there are many widely spaced cables.

3. It is much more difficult to site than a longitudinal shiplift.

4. To avoid excessive earthwork, a transversal inclined plane must be located on a steep mountainside, which makes the construction of the access canals very difficult.

The only modern transversal inclined plane is at Arzwiller (France) on the Marne-Rhine Canal. It has a lift of 146 feet, and a slope of 41%, but the useful size of the container is only 135'x17' (for 350 ton vessels).

The Arzwiller inclined plane was put in service in 1969 to replace 17 closely located locks and to serve as a model for the further development of this type of structure, to be used eventually for high lifts of new French waterways. The location was excellent for a transversal inclined plane, but the several mile long upstream access

canal had to be constructed along a very difficult mountainside (Figure III-OO).

The container travels at a speed of 2 feet/s, with the accelerations and decelerations limited to 0.8 m/s^2. The time necessary for a movement is 40 minutes, barely more than the time required to transit one of the 17 locks replaced.

There is room for a second container on the inclined plane. It would use the same tracks as the first one, to which it would be coupled, but would have its own driving gear and counter weight.

The Arzwiller transversal inclined plane has now been working for 10 years without serious problems. It has shown the way for construction of larger transversal inclined planes.

Water slopes consist of a trench of rectangular section ascending/descending a small incline (less than 5%) and a towing shield supporting a sliding gate.

In front of the shield, the water fills a prismatic volume, having the shape of a wedge, on which the ships can float.

The towing shield moves on two guide paths on each side of the trench. It is composed of two locomotives linked by two cross beams (Figure III-PP).

There is a 44 foot lift water slope on the Garonne lateral canal at Montech (France). It has a slope of 3% and the usable dimensions of the water wedge are 20'x135' (for 350 ton vessels).

Some of the main features of water slopes are:

1. Water consumption is limited to the leakages at the sliding gate.

Figure III-OO

Arzwiller Transversal Inclined Plane

containers

container tracks
counterweight tracks
slope

Hoisting gear
for each container :
12 cables
2 winches ø 3.30m

Counterweights
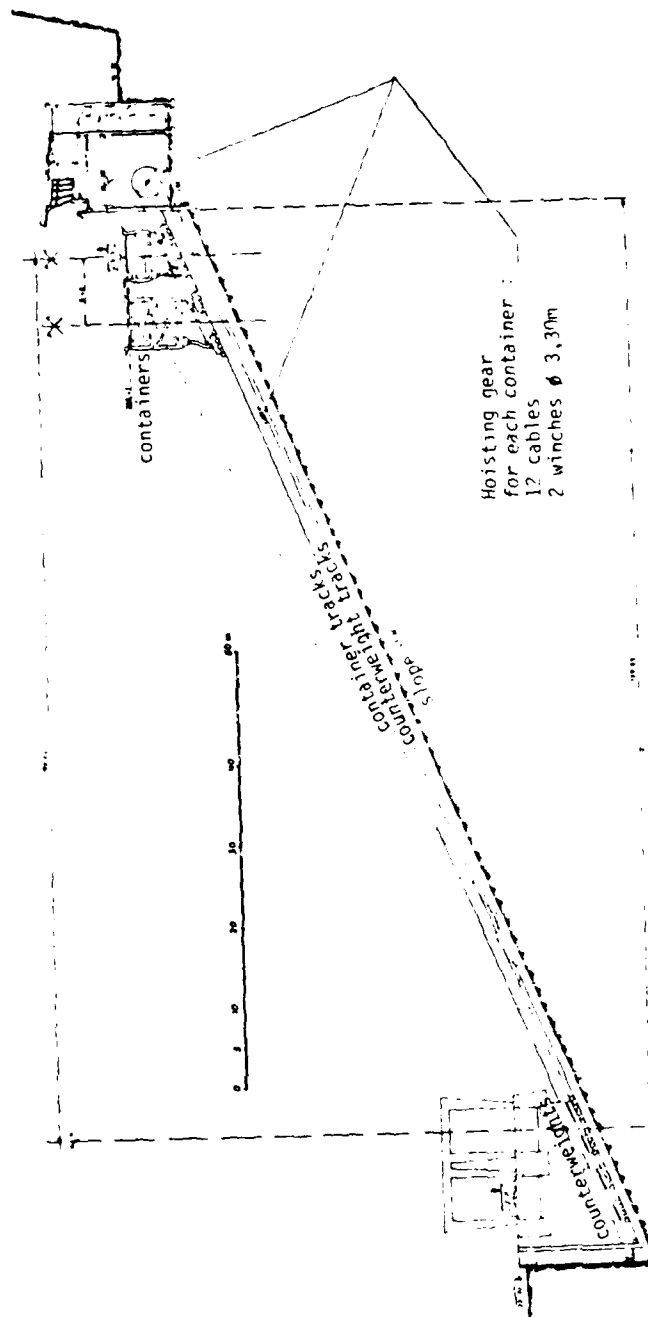
Figure III-PP

Working Principle of a Water Slope

a. The vessel enters the water slope

b. The vessel is ascending

c. The vessel moves into the upstream reach
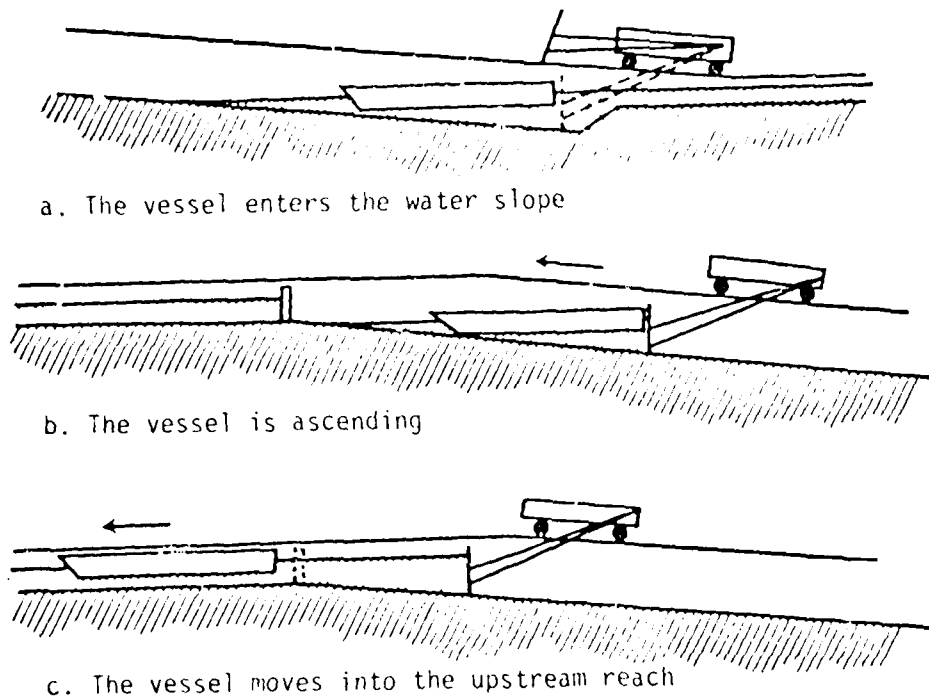
2.   The loads on the structure are variable and very large directly under the towing shield.

3.   The power needed and the energy consumed are very high (about 5 MW for a 1350 ton vessel).

4.   Can be used with variable water levels.

5.   Speed of about 4.6 feet/s and accelerations must be limited due to the movement of the water level in the water-wedge.

Table III-3 summarizes the characteristics of the high lift structures discussed.

TRENDS IN THE FIELD OF
  HEAVY CONSTRUCTION
  APPLICABLE TO LOCK AND
  DAM CONSTRUCTION

During recent years, heavy construction benefited enormously from the technological progress and widespread use of prestressing techniques within the construction industry. This resulted in a variety of uses for pre-stressing rods and tendons being developed as earth tie-backs, as rock anchors in excavation support systems, as members resisting lateral and up-lift forces, to solidify the subsurface soil strata and to stabilize fissured rock formations. This was possible due to the development of new anchoring devices, tensioning equipment, grout and grouting procedures. The other aspect of prestressing, which influenced heavy construction, namely construction of deep foundations, is the development of prestressed concrete piles and their driving techniques. Several other innovations, such as slurry wall construction, drilled pier foundations, vibroflotation, and reinforced earth, were made possible due to advancement of the theory of the soils mechanics, the use of the new materials and the development of modern construction equipment.

All the above mentioned construction procedures are applicable to lock and dam construction. Several of these methods are currently being more commonly used either for the construction of new locks and dams or for the rehabil-itation of existing ones. The following section discusses these previous applications and points out other potential

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Table 111-3
Characteristics of Some High-Lift Structures

Location	Name of River/Canal	Type of Structure	Usable Length m	Width m	Depth m	Lift m	Rising Speed m/s	Remarks
St Pierre (France)	Rhone Riv.	Lock	195	12	3.50	26	0.027	max. speed . 0.058 m/s
Uelzen (West-Germany)	Lateral Elbe Can.	Lock	190	12	3.50	23	0.03	3 water saving basins
John Day (U.S.A.)	Columbia Snake W W	Lock	205	26.2	4.50	34	0.054	
Ust-Kamenogorsk (U.S.S.R.)	Irtysh Riv.	Lock	100	18		42	0.026	filling time .27 min.
Leerstetten (West-Germany)	Main-Danube Canal	Lock	200	12	4.00	25	0.021	max. speed . 0.029 m/s
Carrapatelo (Portugal)	Douro Riv.	Lock	85	12	4.20	34.5	0.044	
Lueneburg (West-Germany)	Lateral Elbe Can.	Cable Shiplift	100	12	3.50	38	0.24	accel.:0.12 m/s^2
Henrichenburg,Germ.	Dortmund-Ems Canal	Floating Shiplift	93	12	3.50	14.50	0.15	accel..0.01 m/s^2
Thieu (Belgium)	Centre Canal	Hydraulic Shiplift	41	5.8	2.40	16.90	0.04	
Niederfinow (East-Germ.)	Oder-Havel Canal	Cable Shiplift	85	12	2.50	36	0.12	
Strepy (Belgium)	Centre Canal	Cable Shiplift	100	12.5	3.50	73	0.20	to be built soon
Arzviller (France)	Rhine-Marne Canal	Transversal Inclined Plane	41	5.2	2.90	44.50	0.60	accel. 0.02 m/s^2 slope 41%
Krasnoyarsk (U.S.S.R.)	Jenissei River	Longitudinal Inclined Plane	90	18	2.20	130	1.35	automotive slope : 10%
Ronquieres (Belgium)	Charleroi-Brussels Can.	Longitudinal Inclined Plane	87	12	3.70	68	1.20	counterweights slope : 5%
Strepy (Belgium)	Centre Canal	Longitudinal Inclined Plane	100	12.5	3.85	73	1.50	Unconstructed project slopes . 5 or 10%
Montech (France)	Garonne lat. Canal	Water Slope	41	6	2.50	13.30	1.40	accel.:0.01 m/s^2 slope 3%
Strepy (Belgium)	Centre Canal	Water Slope Project	100	13	3.50	73	1.75	accel..0.025 m/s^2 slope : 3.5% power : 8.4 MW Unconstructed

applications of the above mentioned techniques in lock and dam construction.

(a) Earth Tiebacks

The use of tiebacks in cofferdam and sheet pile wall designs is finding application in the construction of approach guide walls, mooring cells, and steel sheet piling (temporary) types of locks.

The general principle consists of drilling inclined holes into the soil which is to be retained. The holes must be extended into the material beyond the wedge of soil that may act to push itself and the lining wall into the excavated area. High tensile strength bars or cables are inserted into the hole and grouted to provide safe anchorage to the soil mass outside the potential zone of slippage. Figure III-QQ shows five types of tiebacks that have been employed successfully.

Each tieback is then preloaded by prestressing. These are successfully employed for protection of deep excava-tions using H-piles, steel walers and timber lagging as temporary or permanent bracing. The method also lends itself to the support of sheet piling walls or concrete retaining walls (which could be built by a slurry-trench method). Among many advantages the system offers for lock and dam construction is the possibility of monitoring the anchor forces due to redistribution of stresses in the soil corresponding to changes of water elevation in the river. If the anchor slips excessively, installation of additional tiebacks is feasible as long as group action does not render it ineffective. For permanent application of tiebacks, an effective corrosion protection of anchors and the unbonded portion of the tendon is essential.

Another application for earth anchors can be found in resisting large uplift pressures created by dry-dock type lock construction. A method to reduce such stresses con-sists of anchoring the floor of the lock to the underlying soil by means of closely spaced tension piles. This method is especially advantageous when the soil underlying the lock floor is soft, so that piles are needed to support the floor when the lock is filled with water. The

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Figure III-QQ

Earth and Rock Tiebacks
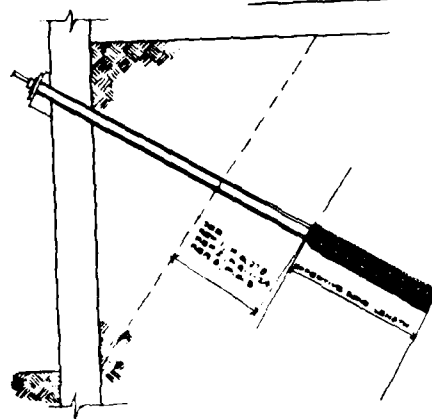
Soil anchor, bond length location
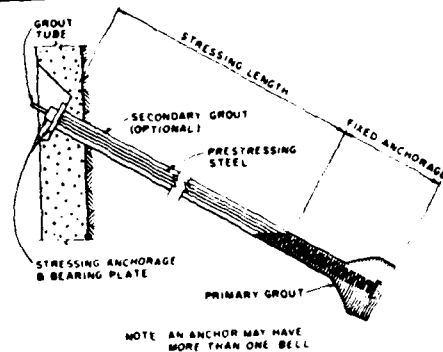
Belled soil anchor
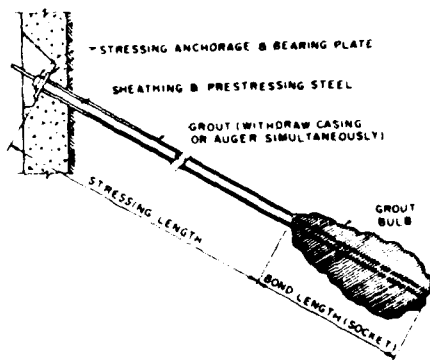
Pressure grouted soil anchor
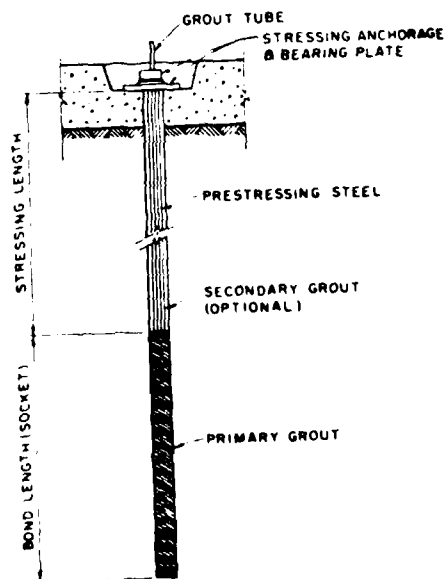
Rock anchor
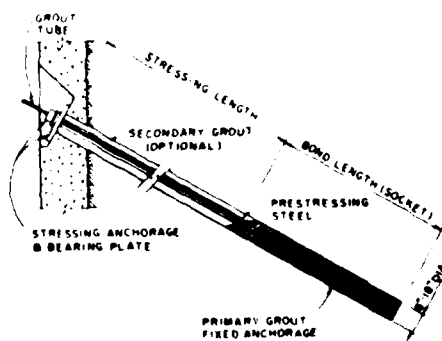
Augered soil anchor

piles act as tendons to counteract the uplift forces supporting the floor slab, and they act as friction piles in the opposite direction to support the lock structure.

A special type of dry-dock floor anchorage was used in the North Sea Harbor of Emden, Germany (Figure III-RR). Steel sheeting was driven around the outer perimeter of the dry-dock and braced internally, the ground water was lowered by means of deep wells, where upon the excavation was performed; 496 reinforced concrete anchor cones, with their cables attached, were then sunk by vibroflotation, compacting thereby the entire originally loose sand deposit. The anchor cables received a seven-poly corrosion protection. After the reinforced concrete floor was cast, each cable was prestressed by a 105 metric ton load. The cable connections to the floor slab were designed to permit later access for checking of the prestressed load. This method ensured that the entire buoyed weight of the compacted sand mass above anchorcone level continued to act as an integral part of the floor slab in resisting uplift pressures.

(b) Tiebacks in
     Rocks - Rock
     Anchors

Tiebacks in rock are based on the same basic principles as tiebacks in soil. However, the superior anchorage that can be developed in rock leads to tieback forces that may be 10 to 20 times as large as for anchorage in soils. Permanent anchorage to rock has been used to solve stability problems in existing and new dams and foundations for buildings, bridges, and other structures.

Another use of rock anchors is in the stabilization of rock beds if rock undercutting is necessary or in the improvement of fissured rock to support foundations. Many locks and dams in the United States are founded on bedrock, therefore, the application of rock anchors to enhance stabilization is a viable consideration. The interface between foundation and supporting medium is of particular interest, because the inability to develop net

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Figure III-RR

Section of dry dock in Emden. When dock is empty floor uplift is resisted by prestressed cables (b) of anchor cones (a) sunk through sand by vibroflotation. (From Agatz and Lackner)
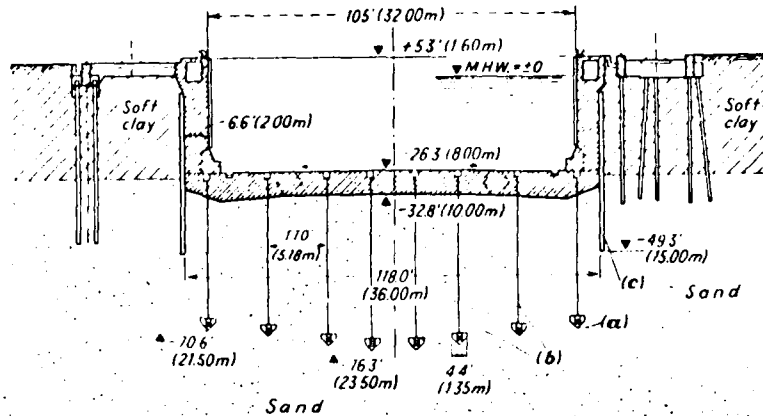
compression forces may lead to partially open joints. The problem may be open joints under water or lack of sufficient weight to prevent sliding under extreme loading conditions. In the past, this led to design of very massive and expensive structures (concrete gravity dam and gravity wall type, or heavy dry-dock type locks). The usefulness is demonstrated in rehabilitation work on older dams such as Harlan County Dam in Nebraska, La Prele Dam near Douglas, Wyoming, and Conorvingo Dam on the Susquehanna River (see illustrations on Figures III-SS and III-TT) At these dams, the rock anchors were secured in compctcnt rock beneath the dams and post tensioned to counteract uplift forces.

(c) Trends in
Foundation
Engineering

Several methods of strengthening weak foundations have been developed recently. One of the methods suitable for improvement of large areas of loose granular deposits is

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Figure III-SS

Dam Anchored to Rock Using Post-Tension Tendons
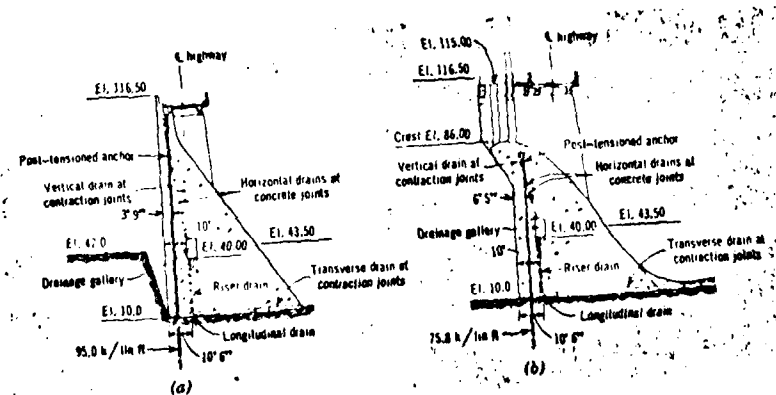
Figure III-TT

Dam Anchored to Rock Using Post-Tension Tendons

Photo A Holes (34" diameter) were bored into spillway crest to provide recess for tendon anchor block. After anchor installation, holes were backfilled with concrete, so original spillway surface shape could be restored

Photo B Multi-strand cable tendons, some up to 195' long, were unrolled from track-mounted drum and inserted into hole

Fig 4 Tendons in powerhouse monoliths were located only at piers, specific locations were limited by gantry crane rails, trash rack rails vent shafts, etc.
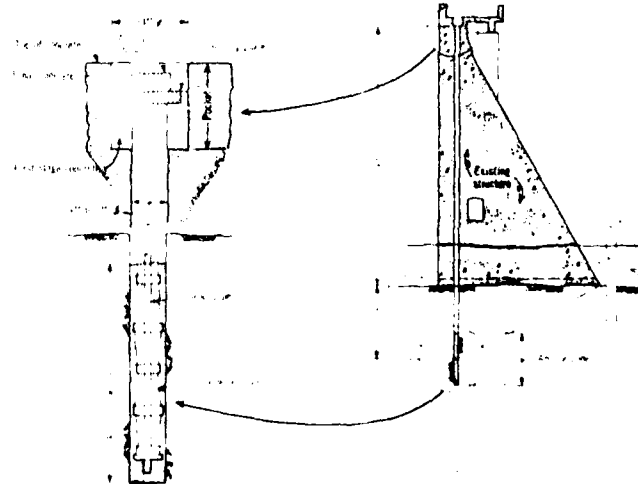
Fig 5 Details of anchor installation. For each anchor, 34" pocket was cut, than 6.7" hole was drilled to anchorage depth. Each hole had to meet straightness, verticality, and watertightness specs Bearing plate and first stage concrete were installed, tendon was lowered into hole, and anchor zone was grouted. After grout reached required strength, tendon was stressed, locked off and trimmed Job was finished by filling hole with grout and placing final concrete

vibroflotation and vibroplacement. The method lends itself very well for improvement of foundation conditions for the construction of locks and dams on sites where loose sands and gravels are overlaying firm soils or bedrock.

Vibroflotation was successfully used on such large projects as the expansion of dry-dock facilities in Newport News, Virginia, for the Newport News Shipbuilding and Dry-Dock Company.

The method of vibroflotation compacts loose granular deposits by using deep vibrating probes. This results in an increase in the relative density of granular material and a corresponding increase in sheer strength.

A variation of vibroflotation is vibroplacement, which is a technique for improvement of the strength and settlement characteristics of weak cohesive materials. The vibrating proble - "vibrofloat" - is lowered into weak soils with the help of water jets. The soil disturbed and displaced by this process is then replaced by coarse granular fill, which is thoroughly compacted and displaced into the surrounding soil. Using this process, a stone column is formed with a dense, coarse grained material, with a surrounding zone of strengthened, existing soil. Depending on the consistency of the natural soil, columns of two to four feet in diameter are obtained.

The use of Bentonite Slurry is an innovation, which is finding widespread application in heavy construction and in the construction of locks and dams. Called the Bentonite Slurry Trench Method, the technique was developed for civil engineering work in Europe in the early 1950's but is still relatively new in the United States. It relies on the simple concept of balancing the pressure exerted on the walls of an excavation with the pressure of a fluid. The fluid in this case is a watery mixture of slurry created by mixing water with a highly absorptive clay called bentonite which expands to many times its original volume when mixed with water. The slurry prevents the intrusion of ground water and the collapse of the sides of the trench.

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Slurry walls economically replace sheet piling, which is presently used in the construction of locks to form cut-off walls, to provide protection against scour, to confine foundations and to prevent undermining, erosion, and underseepage.

Slurry walls can also provide a watertight cut-off that permits an excavation to be made without lowering the ground water outside of the construction area, enabling construction in the dry. Slurry walls have been used as impermeable cut-offs on several construction sites in the United States. A 7000 foot slurry trench has been used to encircle the construction site of a new concrete lock on the Tennessee-Tombigbee Waterway in Alabama. It formed an economical water cut-off which allowed excavation under dry conditions. The 44 inch wide trench was excavated to depths ranging from 20 to 55 feet and was keyed into impervious shale. At another site, Gainesville Lock and Dam in Alabama, the Caisson Corporation installed a 500 foot slurry trench to seal off an area where a concrete spillway was to be built. The trench was 44 inches and excavated to a depth of 30 feet.

Concrete filled slurry walls can be load bearing permanent walls, tied back to eliminate internal bracing and installed without the need of steel sheeting or other retaining systems. (See Figure III-UU for illustration.)

Large diameter drilled pier foundations may also find economical application in locks and dam construction. Pier shafts 10 feet in diameter and under-reamed to 20 feet or larger are feasible to install with modern equipment. Drilled piers may be lowered to depths of up to 150 feet, if necessary, to reach sound bedrock. If under-reamed, they can provide very stable foundations resisting vertical, lateral or uplift forces. They could be used in lieu of piles to support lock or auxiliary walls. They can provide an economical foundation for cellular auxiliary walls.

In moist or saturated soil conditions or in otherwise unstable soils, the drilled hole is prevented from caving in by use of bentonite slurry. The slurry enables the driller to under-ream even in a clean sand below the water

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Figure III-UU

Concrete Filled Slurry Wall
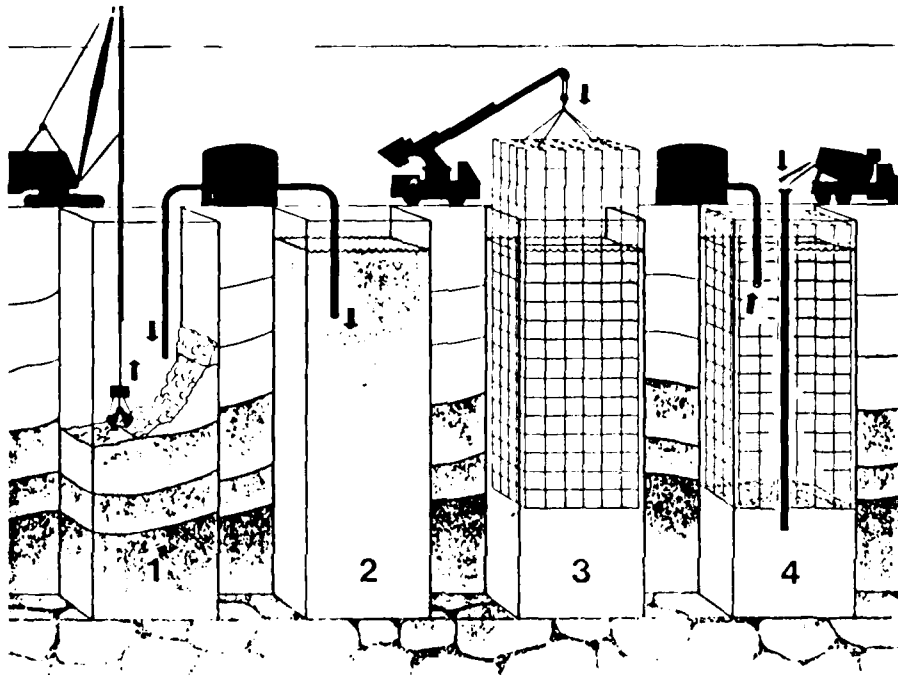
table, without any caving or sloughing of the roof of the
under-reamed. After the drilling is completed, a rein-
forcing cage is lowered into the slurry and concrete is
tremied to displace the slurry.

The use of reinforced earth is another concept which
might be applicable to the construction of guide walls and
can be economically competitive with other structural
systems presently in use. Reinforced earth is a con-
struction material formed by the assooiation of soil with
linear metallic reinforcements. This method was developed
in France and patented by Henri Vidal.

The principal of reinforced earth lies in the ability
to activate sufficient functional resistance within the
soils mass to develop tension within the longitudinal
reinforcing members without causing internal shear of the

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soil. This concept offers a vertical retaining wall,
which on its face consists of precast concrete elements
which form an interlocking system. (See Figure III-VV).

Figure III-VV

Reinforced earth retaining wall under construction

(d)   Precast and
      Prestressed
      Concrete in the
      Construction of
      Locks

Economies may be achieved by precasting various
elements of a lock structure and/or by precasting entire
segments of locks and assembling them by using post-
tensioning and prestressing methods. The application of
prestressing technology to massive structures such as
locks may have several advantages. The traditional rein-
forced concrete structures are massive because they are
required to resist large water or earth pressures and
because they must withstand buoyancy forces. Prestressed
concrete can provide more economical slab and wall
sections of lesser thickness, while buoyancy can be
resisted by rock c. earth anchors as mentioned above. On
the other hand, by prestressing of the lock floor slab,
larger spans may be achieved, resulting in a wider lock
chamber. Reinforced concrete structures usually require a
great amount of bonded reinforcement, creating congestion,
high bond stresses, cracking and spalling of concrete.
The rebars are seldom fully stressed to their capacity and
expansion joints must be constructed in order to control
cracking. All the above deficiencies can be drastically
improved by prestressing the structures in all three
directions. The massive structure may be built without
any expansion joints so that the whole structure is homog-
eneous, virtually crackless and watertight. This is the
best possible protection against corrosion of reinforce-
ment and improves resistance and durability.

Prefabrication methods may also be economically used
in lock and dam construction. The best illustration for
various possibilities of application of precasting is in
the construction of the Kreekrak Locks on the
Scheldt-Rhine Connection in the Netherlands.

The Kreekrak Locks, constructed in accordance with a
salt and fresh water exchange system with gates closed,
differ in many respects from a conventional lock design.
In particular, the locks are double-bottomed. Under each
lock there is a culvert for saltwater supply and removal.

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The lock is separated from the culvert by a perforated floor; the floor is designed to ensure proper distribution of the flow and was prefabricated (see figure III-WW).

Figure III-WW

Kreekrak Lock - cross-section of lock chamber

CROSS-SECTION OF LOCKCHAMBER
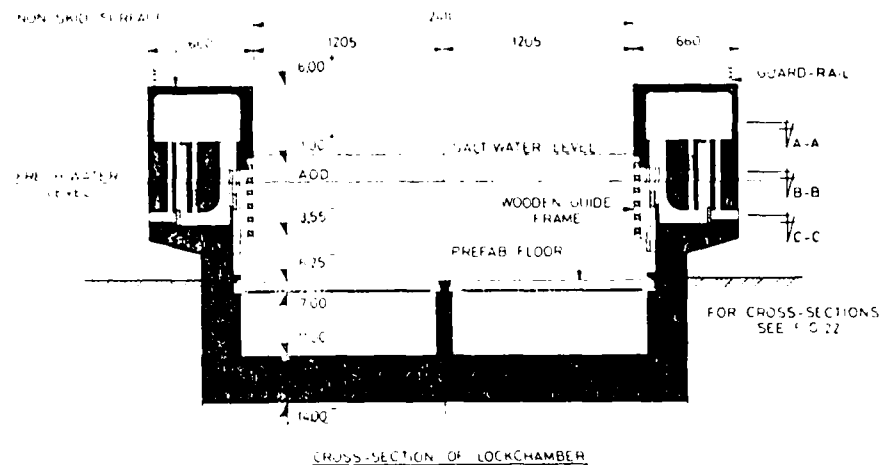
In the Soviet Union, prefabricated reinforced structures are widely used in the construction of large locks, such as at the Kiev Hydroelectric Power Station on the Dnieper River where prefabricated concrete accounted for almost 24% of all concrete in place.

The idea of prefabrication can be carried even further. Entire large segments of locks can be precast in a river bank construction yard. The segments could then be floated down the river to the proposed lock site, sunk to the river bottom at the required elevation, and anchored by methods described above. The use of high strength concrete or lighweight concrete should permit the reduction of weight of the lock components, while satisfying all the strength requirements. In softer or cohesionless soils, excavation for a sunken lock could be accomplished by jetting or dredging. The individual segments could then be assembled, tied together by positioning in a similar fashion as in precast cantilever bridge construction.

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An example of this type of construction is the proposed new Inner Harbor Navigation Canal Ship Lock. Siting restrictions on the new lock, which must be rebuilt in the same location as the existing lock, and the necessity to minimize closure of the canal to navigation resulted in the decision to utilize offsite constructed floating lock elements in order to minimize construction time.

Four possible construction schemes with three potential gate types (using sector gates, miter gates and vertically pinned sector gates) have been investigated for this low lift structure, for a chamber length of 1200 feet, a chamber width of 110 or 150 feet and a depth over sill of 31.5, 40 or 50 feet. (Report: "Mississippi River - Gulf Outlet, Louisiana, New Lock and Channels Concept Development Design IHNC Lock Replacement," by Frederic R. Harris, Inc. and Perkins & James Architects, Inc., for the Corps of Engineers, New Orleans District, November 1979.)

The four construction schemes investigated range from construction of the gate sills offsite to construction of the gate bays offsite, complete with operating lock gates, to construction of the gate bays and lock chamber sections offsite, to construction of the complete lock offsite in two sections completely fitted out with gates and gate operating machinery. While all of the schemes appear to be feasible, a final design concept has not been selected for detailed investigation. Thus, details of the prefabrication technique to be employed, which will undoubtedly include the consideration of relatively new prestressing techniqucs, new high strength/lightweight materials and new construction techniques, have not yet been formulated.

TRENDS IN THE COST OF
    NAVIGATION LOCKS AND
    DAMS

As a result of technological improvements in the design of locks and dams over the past several decades, navigation safety has improved, service times have decreased, maintenance requirements have decreased and operation has improved. Savings in these areas resulting

from the improvements are believed to have offset the increased construction costs which in many cases have resulted.

For example, the use of model studies to facilitate the design of approaches has resulted in designs which are greatly improved in terms of safety and required time of approach. However, use of auxiliary walls of improved design and the incorporation of wing dikes, submerged dikes, sheet pile cells, and training structures have increased the cost of lock facilities.

It is likely that continued investigation to improve the safety, and other aspects, of lock facilities will result in additional improvements which will add to the cost of the lock facility. However, as additional work is performed to generalize design for gates, valves and filling systems, the engineering cost to develop or adapt these designs on a site specific basis will be reduced. For example, the design for the side port filling system has been developed to the point where model tests are not required to design these systems for normal conditions and for the applicable range of lifts for three sizes of locks.

The cost of locks and dams may be reduced as new heavy construction techniques discussed are applied in the construction of lock facilities or as additional techniques are developed. The use of some new techniques may actually increase costs, as it may be possible to develop new designs which were considered infeasible using conventional construction techniques (the offsite prefabrication construction of lock segments to be floated into place, for example.

In addition, in recent years it has become necessary to consider more alternatives and carry the development of the alternatives further than ever before. This has resulted in increased engineering costs and consequently increased lock costs.

Lock and dam construction costs were provided in the report "Analysis of Waterways System Capability." Costs,

as presented in the report, can be adjusted to reflect changes in technology suggested in this task.

It is expected, however, that as more public funds are available, the quality and reliability of navigation structures will improve and the associated cost of navigation structures would increase.

ONGOING RESEARCH

As was previously mentioned, in order to ensure that lock and dam facilities will function satisfactorily after construction, hydraulic model studies are absolutely essential. However, due to the high cost and great area requirements of model studies, a great deal of work in recent years has been focused on reducing the need for model studies or, at least, reducing the number and extent of model studies which must be performed for a given project.

The recently published Draft Engineering Manual, "Layout and Design of Shallow Draft Waterways " (EM 1110-2-1611, 1979), prepared by the Office of the Chief of Engineers in conjunction with the Waterways Experiment Station of the Army Corps of Engineers, attempted to present guidelines for the layout of locks and dams developed by the Corps as a result of experience with model studies, prototype testing and project evaluations. The guidelines presented should reduce the amount of effort required in developing future layouts, both at WES and in the District offices. The manual undoubtedly will be updated as additional experience is gained and research results become available. Along these lines, it would also be a good idea to instrument new locks as they are built in order to accommodate prototype testing in the future.

During the past several years, research has been initiated at WES in the area of developing math models for navigation studies. At WES, an attempt is being made to develop math models which reproduce the results of the prototype tests. Math models, if they can be developed to adequately simulate vessel movement under assumed conditions, could be very useful in reducing the considerable

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time and expense which is associated with physical model-
ing. Unfortunately, there appears to be three dimen-
sional effects which math models alone cannot adequately
model at the present time. However, by using limited
physical models to calibrate the math models, it may be
possible to develop math models, first, sufficiently to
use them as a screening device to reduce physical modeling
requirements and eventually to eliminate physical modeling
for some situations.

While at the present time research is limited to
developing models for vessel powering and maneuverability,
such research could eventually lead to the development of
rational design criteria for approaches and entries.

IV - METHODS OF INCREASING THE
CAPACITY OF EXISTING LOCKS

This section assesses methods which can be used to increase the capacity of existing locks. In recent years many measures have been found to be effective in increasing the throughput capacity of lock facilities. Whenever these measures could be implemented successfully they have been regarded as an attractive means of postponing costly lock reconstruction. This has prompted a number of additional methods to increase capacity to be suggested, both in the United States and overseas but, to date, the feasibility and effectiveness of most of these methods has not been fully established.

In the National Waterways Study Report "Analysis of Waterways System Capability" a list of possible measures which could be used to increase the capacity of existing locks was presented. Included was a brief description of each measure. In this report, the measures are discussed in terms of their relative potential for increasing capacity and the feasibility of their implementation. As much as possible, the discussions that follow are based on the results of existing studies and evaluations.

While any or all of the measures listed in the report "Analysis of Waterways System Capability" could potentially increase the capacity of some locks, it is important to put the measures into perspective. Many of the measures have been well proven to increase capacity and are routinely incorporated into designs for new locks or routinely added as part of maintenance or rehabilitation at existing locks. Some measures have been found, through limited site testing or theoretical analysis, to provide benefits at high traffic levels and can be recommended as effective when site conditions permit. Other measures have been investigated but, while shown to be potentially effective, have never been implemented, for a variety of reasons. Still other measures, with seemingly great potential, have never been investigated or seriously considered because of a lack of basic research which is required to prove the feasibility of their implementation or because of potential adverse implications or high costs associated with their implementation. Measures which would require the towing industry to change its operating

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practices or place major operating restrictions on the towing industry necessarily fall into this final category.

The technical maximum capacity of a lock is defined as the theoretical maximum tonnage of cargo which can move through the lock, or which the lock can process, per unit time. The capacity is therefore a function of the following:

     1.   the size of the lock (physical dimensions).

     2.   the time required to process a tow.

     3.   the distribution of tow sizes and tow configurations using the lock.

     4.   the percentage of empty backhaul.

     5.   the time the lock is available for commercial operation.

However, theoretical maximum capacity of a lock can rarely be achieved because extreme delays are often incurred. The practical capacity of the lock can therefore be much lower than the maximum capacity.

Accordingly, there are several ways in which the practical capacity of a lock can be increased:

     1.   decrease tow processing time.

     2.   improve tow arrangements and tow size distribution.

     3.   even out seasonal distribution.

     4.   increase lock availability.

     5.   provide replacement locks of larger dimensions.

     6.   improve the channel by increasing authorized channel dimensions, or increasing the reliability of authorized dimensios and, as a result, increase accommodated tow size/tonnage.

Of these measures, only decreasing tow processing time (lock service time) per ton of cargo by minor structural and non-structural means can be reasonably implemented to provide uniform benefits without major investments and without drastically changing operating procedures. (Note: there appears to be little opportunity to increase the availability of locks, as downtime for mainatenance is generally negligible and downtime due to accidents and rehabilitation is rare. The possible exception to this would be proposed extensions of the navigation season. See Section VIII.)

The tow processing time, or lock service time, is that amount of time which a tow controls the lock, i.e., prevents the lock from being used or readied for use by another tow. It is that time from when a tow finds, upon the exit of the tow ahead, that it can proceed into the lock, be locked, and depart to that point at which the opposite bound tow may start to enter the lock or at which time the lock may be readied to accept the next tow in the same direction. To keep tow processing time as short as possible and thereby increase the number of lockages in a given time period to maximize the practical tonnage capacity, it is important that all elements of that time interval be kept at their maximum. The tow processing time varies with the type lockage (single, double, setover or knockout), the type of entry/exit (fly exchange, turnback) and vessel size, load, etc.

At existing locks only the chambering time, which is the time required to open and close the gates and to fill and empty the chamber is under the direct control of the Corps lock personnel. All other elements of the lockage interval time are primarily under industrial control and are only affected by Corps operating personnel in as much as lockage procedures can be established and enforced, additional facilities (such as mooring cells and switchboats) can be provided, or approach channel design can be improved.

Approach distances at many existing locks are very long because hazardous conditions exist which cannot be economically rectified. On the other hand, many older locks often suffer from difficult approaches and long chambering and gate operating times as a result of

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insufficient knowledge at the time of construction, inefficiencies due to age and lack of modernization and changes in operatng criteria. Inefficiencies and difficulties which act to reduce the overall lock service time are generally not investigated for improvement and investment until such time as traffic delays are encountered. When traffic delays do occur, they re often relieved by employing techniques already employed at other locks. Thus, the state of modernization or the level of non-structural improvement of existing locks generally varies from lock to lock as a function of traffic.

METHODS WHICH ARE
CURRENTLY USED TO
INCREASE LOCK CAPACITY

The following paragraphs discuss measures which have been proven effective and are used to increase the capacity of locks. Some of the measures are routinely employed at new locks as part of modern lock design, but, to date, have not been universally applied. Other measures have been shown to be effective at high traffic levels and are currently employed at congested locks when their application is justified by local conditions.

It has been noted that the cost of constructing locks has been steadily increasing (independent of inflation) as a result of continuing improvements to lock designs (see Section III - Trends in the Cost of Navigation Locks and Dams). The increased capital costs have resulted in increased safety, decreased maintenance, improved operations, and decreased service times for modern locks. The decision to incorporate a specific improvement into a new lock involves comparing the increased cost to the benefits derived from all of the above factors. In many cases, however, the magnitude of the improvements effect on service time cannot be quantified so that the decision to implement on improvement whch may reduce service times depends upon the value of other possible benefits, such as those just mentioned. Once implemented a reduction in service time is possibly achieved but usually not measured.

In recent years, significant delays have occurred due to congestion at several locks in the United States, specifically, Lock and Dam 22 and Lock and Dam 26 on the

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Upper Mississippi River, Gallipolis Lock on the Ohio
River, Marseilles Lock on the Illinois Waterway, Bonne-
ville Lock on the Columbia River, Winfield Lock on the
Kanawha River, Kentucky Lock on the Tennessee River, and
Inner Harber, Vermillion, Calcasieu and Algiers Locks on
the Gulf Intracoastal Waterway. Studies which have been
initiated to evaluate the potential for increasing lock
capacities at high traffic levels have been oriented
toward developing improvements for these locks. The bene-
fits afforded by measures investigated for increasing the
capacity of the above locks could also probably be gained
at other locks. However, to date, all quantitative re-
sults have been obtained for the specific locks investi-
gated so that in order to identify the benefits (in terms
of increased lock capacity) possible at other locks, site
specific information must be obtained. The development of
generalized relationships which could be used to evaluate
the relative benefits and costs of these measures would be
highly desirable and facilitate their investigation at
other sites.

(a) Improvements in
     Lock Operating
     Equipment

Because of the age of the equipment at most locks
which have developed to the point of having high traffic
levels, the existing machinery is understandably ineffi-
cient. Investment in new or modern hydraulic operating
equipment or improvement of equipment could in many
instances decrease entry, exit and chambering times.
These components of lock service time, in most cases,
represent only a portion of the total service time, but
minor savings in these areas can have a significat effect
on capacity. In cases which have been investigated be-
cause of apparent gross inefficiencies in operating equip-
ment (i.e., with potential for major service time reduc-
tions) the resulting abnormally long lockage times have
often been found to be due to specific conditions at the
lock which required slower than normal operating times.
For example, at Marseilles Lock, on the Illinois Waterway,
it was found that abnormally long filling times were a
result of regular clogging of intakes. This condition
could be mitigated by other means, such as automated trash
rakes, an air bubbler system or an auxiliary wall to redi-
rect flow (at Marseilles Lock). In other cases operating
equipment may not be operating at normal speeds in order

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to avoid excessive turbulence or unsafe conditions. These are conditions which generally require structural modifications to the facilities to improve hydraulic conditions and are generally considered to be costly.

It is advisable to continue to investigate on a case by case basis locks which have abnormal filling, emptying and chambering times. In this way, the reasons for the inefficiencies can be identified so that measures to improve service times can be proposed. The implementation of measures to provide major reductions in equipment operating time will continue to provide major benefits at some sites. Likewise, minor improvements to several components could, in combination, provide major benefits.

It has also been suggested that the life and efficiency of the operating equipment could conceivably be prolonged if the machinery were operated in accordance with the design. This implies improved dialogue between designers and operators. On the one hand, each lock should have an operating procedure prominently displayed before or above the place where the operator handles controls. On the other hand, the lock should be occasionally inspected and operating procedures modified from time to time as conditions at the lock change. This should be the goal of the periodic lock inspection program mandated by OCE.

Improper valve operation of filling systems can cause disturbances that are dangerous to tows or pleasure craft in the lock. In particular, some filling system require very close coordination of valve operations to handle large amounts of water efficiently and rapidly and for the safety of the craft in the locks. The correct sequence of operations for a variety of conditions, both usual and emergency, should be displayed. Trouble indicators and the potential problem behind them should be displayed so that emergency procedures or requests for technical assistance can be initiated when serious problems arise.

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(b)   Improving Lock
       Approaches

The time required for the vessel to leave the waiting
area and to become properly aligned for entrance into the
lock chamber (lock approach time) is a major portion of
the total lock service time. As such, any modifications
which can be made to reduce the approach time can have a
significant effect on capacity.

Recognizing this fact, a great deal of effort has been
expended to develop designs for lock approaches to provide
ideal conditions at new locks. Ideal approach conditions
permit fully loaded tows to become aligned for approach
into the lock some distance from the lock and then drive
or drift toward the guide wall with little or no
maneuvering or engine reversal required (see Section III -
Navigation Lock Design).

Several aspects of modern approach design were
discussed in Section III; however, many of these aspects
can also have direct application in the improvement of
existing approaches. Items which are currently analyzed
at new sites to optimize approach designs are as follows:

       1.   alignment of the approach channels with
respect to local currents.

       2.   installation of auxiliary walls.

       3.   installation of training structures to
realign local currents.

       4.   installation of submerged dikes.

       5.   installation of guard cells angled towards
the center of the river from the upstream end of the river
guard wall.

       6.   extension of the guard/guide walls.

       7.   installation of wing dikes to reduce
sedimentation in the lower approach.

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8. provision of mooring cells.

9. elimination of obstructions.

10. installation of structures to reduce the effect of powerhouse operations.

Many of these items could be incorporated into existing lock facilities in order to reduce approach times. However, prior to realigning channels and providing auxiliary structures, it is necessary to fully understand their effect on local currents. At the current state-of-the-art, this would, in most cases, require model studies to be performed or detailed site investigations to be undertaken. (See Section III - Navigation Lock Design for the current state-of-the-art in the design of approach channels.) The possibility of shoaling due to channel modification (especially dike construction) must be carefully considered at each site.

For fiscal year 1981, several work units have been proposed by the Waterways Experiment Station of the Army Corps of Engineers to study means to minimize the effect of hydropower generation on navigation. It is likely that measures to reduce the effect of hydropower releases on tow movements in approach channels will be developed.

(c) Provision of Mooring Cells

Currently, active programs of mooring cell construction at existing locks are being undertaken or have been completed in a number of Corps Divisions (i.e., ORD, LMVD, SWD, NPD, NCD). The mooring cells are constructed at the lock approach points (usually a remote area where vessels await their turn to lock) in order to improve the safety of the vessel during high flow or emergency conditions. Where cells are available, vessels can tie up while awaiting their turn to lock so that less energy is expended while idle and less clearance is required for vessel passing. During low water levels, there is some evidence that with the engines idle few bottom and bank sediments are resuspended because less maneuvering is performed when mooring cells are available.

As an additional benefit, because required safe passing clearances are reduced when one vessel is moored, there is potential to construct the mooring cells closer to the lock rather than at the existing approach points and thus reduce approach times. Wherever mooring cells are to be installed, the possibility of moving them closer to the lock should be seriously considered because of possible savings in approach times and the corresponding potential increase in capacity. In considering this possibility, the maneuverability of the tow must be studied with respect to currents in order to allow adequate room to maneuver into the lock. The ability of a tow to power into the lock entrance is not well documented so that lock approaches must still be designed for the tows to drift into the lock. This limits the ability to place mooring cells in close proximity to the lock. An additional benefit at high traffic levels which can be gained from the construction of mooring cells should be noted. When a lock becomes congested such that pilots tying up their vessels at the mooring cells expect a wait of several hours, any reconfiguration which may be required to pass the lock or which may save time during the lockage process can be performed with the aid of the mooring cells. In a similar fashion, mooring cells can also be of value if operating procedures are involved which encourage tows to lock as singles or to improve their lockage configuration (see (1) Ready-to-Serve Policy and (f) Give Priority to Faster Locking Tows in the next sub-section).

(d) Wind Deflectors

In some locations, wind has an adverse effect upon the ability of tows, especially empties, to approach locks. This increases approach (and sometimes exit) times somewhat.

In some cases it may be advisable to elongate the guide walls providing more room for the tow to maneuver into position. In other cases lightweight wooden structures, acting as windbreaks, may reduce the effects. This has been done effectively on some European locks. The possibility of placing natural windbreaks, such as trees, in order to shield the approach area should be considered.

(e) Greater Use of
Radar Reflectors

Under adverse weather conditions, a considerable
amount of time is lost as vessels must approach and enter
the lock at much slower speeds. The installation of radar
reflectors at bridges, on the end of dikes, and on other
obstructions in channels is becoming a widespread practice
as these relatively inexpensive devices greatly enhance
the safety of vessel movement. As most towing vessels are
now commonly equipped with radar, the generous usage of
radar reflectors in approach channels could speed vessel
movement in periods of poor visibility. The benefit of
these devices would depend upon the amount of time visi-
bility is reduced and the severity of approach conditions.

(f) Tow Haulage
Equipment

At locks which are not already so equipped, tow haul-
age equipment can be used to reduce the time required for
double lockages. For some years, various locks have used
a cable assembly to pull the first half of a split tow out
of a lock, thus permitting the towboat and second half to
follow through immediately behind.

A system of wheeled, movable mooring posts (a travel-
ing kevil or towed mooring bitt) can be useful in moving
tows into, through, and out of locks. This system would
reduce the time required for double lockages by pulling
the first half of the split tow out of the lock, like the
cable assembly, but it can also be used to speed entry.
By providing positive control to the tow, the reduction in
damage to walls and corners appears to make this a worth-
while item for consideration at some locations. However,
there are also disadvantages. It has proven to be very
difficult to develop designs that: prevent encroachment
and interference to miter gate recesses; prevent obstruc-
tion to floating mooring bitts; do not adversely affect
location and arrangement of guard rails on the lock wall;
and finally, develop enough tractive force to be effec-
tive. Some of the above problems can be minimized or
overcome if towed mooring bitts are considered in the
initial design and integrated with the other lock fea-
tures. A towed mooring bitt was installed at Guntersville
Lock on the Tennessee River during its construction in the
early 1960's. Since that time, towed mooring bitts have

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been sucessfully retrofitted on several locks on the Tennessee River and at Barkley Lock on the Cumberland River. It should be noted, however, that the majority of the add-on tow haulage units are safety hazards due to possible whiplash from breaking cables.

Conventional haulage equipment does not generally provide as great a benefit as helper boats although their purposes are nearly identical (i.e., to reduce the time for double lockages). In locations where tows longer than the lock do appear but there is no long waiting line, such devices are helpful. At locations where waiting lines develop, the advantage afforded by haulage equipment is reduced because the tow must remake while blocking the gates. Use of an extended guide wall and a N-up/N-down procedure in conjunction with tow haulage equipment would allow tows to remake while not interfering with the operation of the gates for turnback lockages. However, installation of a traveling kevil (rather than conventional haulage equipment) would probably be necessary to obtain capacity increases of the same order of magnitude as with helper boats. At locks which do not experience double lockages, haulage equipment is of limited value because only entry and exit times are increased, slightly.

(g) Floating Mooring Bitts

Floating mooring bitts or floating bollards are now routinely installed at new locks. While these devices improve the safety of locking operations, they also reduce the time required to secure tows in the chamber. Further they reduce the demands upon the time of the lock operators, thereby enabling them to expedite operations. Several locks on the Illnois Waterway have been retrofitted with floating mooring bitts and it is highly likely that may other locks could be similarly retrofitted. It should be noted that floating mooring bitts are not intended to be used to brake vessels, however, as deckhands often use them for this purpose, it would be advisable to design them with this inevitability in mind.

(h)   Greater Use of
      the Auxiliary
      Chamber

Increased use of auxiliary chambers should come about naturally as main chambers become more heavily utilized and the delays to tows increase. It will then be advantageous for smaller tows to double lock in the auxiliary chamber, rather than wait for the larger main chamber.

Certain factors often discourage the use of the auxiliary chamber by most tows. Multiple lockage tows would require as many as six lockages in the auxiliary chamber, where as the same tow could transit the main chamber as a double lockage. The processing of multiple lockage tows through the auxiliary chamber can also create unsafe approach and exit conditions for other tows using the main chamber. In addition to small size, the lack of adequate guide walls or guard walls to assist tows while they enter the auxiliary chamber and recouple after lockage may contribute to low utilization. For example, the auxiliary lock at Gallipolis cannot be used by tows at certain times when the main chamber is in use. The present entrance conditions are such that the entire channel must be occupied by the tows entering and exiting from the main chamber. In addition, interference to operations in the auxiliary chamber is caused by portions of tows secured on the main chamber guide walls during double lockages.

The most effective way to decrease interference between chambers is to construct an auxiliary wall between the chambers. This, however, disrupts navigation during the period of construction. A measure which prohibits tows from reconfiguring on the guide wall is also effective.

If interference with operation of the main chamber is not a problem, or if structural modifications, such as the extension of the center guide wall, can be made, then non-structural measures to increase lock capacity discussed herein would be equally applicable to the auxiliary chamber.

At high levels of traffic, improved scheduling can potentially increase the usage of the auxiliary chamber.

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Use of a Ready-to-Serve policy, which would insure that all tows require a double cut lock as two singles, would probably increase the number of tows able to use the auxiliary chamber and thus increase utilization.

It should be noted, however, that the auxiliary chamber at most locations is considerably smaller than the main chamber so that the capacity of the auxiliary chamber is only a small portion of the total capacity. Subsequently, improvements to the auxiliary chamber have a much lesser effect on total lock capacity than similar improvements to the main chamber.

i. N-Up/N-Down
    Policy

Currently, most locks operate on a First In/First Out oral up/1-down schedule (FIFO). This simply means that the tows are serviced in the order of their arrival and that no restriction is placed on their barge configuration (tow makeup) or size as they approach the lock (i.e., no remake or reconfiguration of the barges is required until after the lockage process begins).

If the time required to reverse the lock to make a turnback entry is greater than the time required for a fly exchange entry, then an alternate rule could be invoked where a 1-up/1-down procedure would be followed. Under this rule, tows in queue on each side of the lock are served alternately. That is, after a tow traveling in a given direction is locked through, a tow traveling in the opposite direction is next to be locked, thereby eliminating the time required to reverse the lock.

These rules are commonly followed at most locks where waiting lines are not too long. At higher traffic levels, a multi-up/multi-down policy can often increase capacity.

The so-called N-up/N-down rule is effective only if the sum of average times for a turnback exit, a turnback, and a turnback entry is much less than the time for an exchange exit and entry, or if used in conjunction with helper boats or extended guide walls. When this is the case, the lock may be reversed, and a new tow can enter

the chamber faster than two tows can exchange use of the
lock. Even though this may result in more efficient use
of the lock, it often causes increased average delay times
because longer waiting times are imposed on tows that
arrive at the lock sooner than the tows being locked ahead
of them and is only beneficial if a queue is present at
the locks most of the time. The savings possible at a
certain lock can be determined from average lockage data,
and is different for every lock.

A method was developed in the Report "Analysis of
Waterways System Capability" to determine the applica-
bility and effectiveness of this measure given site
specific information.

Additional savings can be made if an extended guide
wall is provided to allow tows to remade without inter-
fering with turnback gate operation.

At Locks and Dam No. 26 in the St. Louis District, the
locks are operated under what is known as a "four-up and
four-down" rule. Under this rule, four upbound tows are
locked sequentially followed by four downbound tows, or
vice versa. If the queue in the pool from which tows are
being locked empties prior to reaching the maximum of four
vessels, tows from the other pool are then selected. For
this policy, it is assumed that the last three tows in se-
quence will approach the lock and, therefore, their entry
will be of the turnback (or short) entry type.

Though this appears to be wasteful since the lock must
be filled without a tow in it (the downstream traffic is
being passed while the upstream traffic waits), there is a
considerable time saving due to certain characteristics of
floating craft. The susceptibility of tows to the influ-
ence of the current, the stern steering characteristics of
water craft, and the great length of the modern tows make
it easier for one tow to follow another in line than to
have two opposing tows pass each other. Therefore, the
so-called N-up/N-down rule sometimes allows several tows
moving in one direction to move through a lock in a shorter
period of time than can the same number of tows that must
pass each other in opposite directions. These one-way
rules could also be modified to "three-up/five- down"
depending on waiting line configurations at a given time.

There is, in effect a "five-up and five-down" rule at Vermilion Lock in the New Orleans District. When waiting lines are long, N-up/N-down rules have also been employed at Bonneville, Inner Harbor, Calcasieu and Port Allen Locks.

At some locks having two chambers, such as Gallipolis Lock, the N-up/N-down rule may be ineffective at increasing lock capacity because tows waiting for a turnback entry block access to the auxiliary chamber. In such cases, additional measures to reduce chamber interference may be required in order to implement on N-up/N-down policy.

During high water periods at some locks, lock turnback times are sometimes shorter because of the smaller difference in water elevation, thus indicating there may be some advantages to implementing this rule at certain times of the year.

The choice of the N-up/N-down policy to be used should consider the probability of having a smaller tow available to lock as the last tow in the series. Tows requiring only a single lockage would not to be recoupled on the guard wall, and thus the first of a series of N tows traveling in the opposite direction could begin its entry much sooner. A priority system could also be instituted to give high priority to single tows as the last in the series.

(j) Use of Switch-
     boat or Helper
     Boats

Where heavy traffic conditions occur frequently, it has been demonstrated that the use of an extra towboat at the lock has been very effective in passing traffic by reducing the time required for double lockages. The lockage procedures for this type of operation requires the switchboat to extract the unpowered cuts from the chamber and to secure the unpowered cuts at a mooring where the recoupling of the powered and unpowered cuts do not interfere with the operation of the lock. A reduction in the exit and clear times for both the unpowered and powered cuts of double lockage tows is possible.

Setover single and knockout single lockage tows can also improve their exit and clear times by having the switchboat assist in extracting the tow. The tows would then be required to move, either under their own power or with the help of the switchboat, to a mooring area before reconfiguring for river travel. The following benefits could be anticipated from a lockage procedure in which the switchboat removed the unpowered strings of double, setover and knockout lockage tows to a mooring sufficiently far from the lock that lock operations would not be impeded by the reconfiguration operation:

   1. exit and clear time for the powered and unpowered strings is reduced since the powered string would not be required to maneuver back into the chamber to complete recoupling.

   2. recoupling of the tow can be accomplished at a mooring where the recoupling operation does not preclude lock operations.

In addition to the normal lock facilities, the switchboat operation requires the use of switchboats and moorings located outside the approaches to the main chamber.

Where an auxiliary chamber is available, a single switchboat can be used in both the upper and lower pools. The switchboat should be given priority service in the auxiliary chamber so that it will be available to extract the unpowered cut of the first tow in sequence after it has completed extracting the unpowered cut of the last tow in the preceding sequence in the opposite direction.

An alternative to this operation is to provide a switchboat in the upper pool and an extended guide wall in the lower pool with a tow haulage unit. When combined with a N-up/N-down policy, this alternative provides nearly the same benefit as having a switchboat in the lower pool while affording downbound tows the added safety of remaking on the lower guide wall instead of at a downstream mooring area.

Switchboats can also be employed when a Ready-to-Serve policy is in effect. Under this policy, sufficient

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switchboats would be required at the locks at all times to assist the larger tows in their locking process. The switchboats would attach to separate unpowered cuts of large multicut tows and serve as the towboat until the barges have been moved to the mooring area on the opposite side of the lock. It was estimated in "Locks and Dam No. 26 (Replacement) Design Memorandum No. 11,"[8] that five switchboats would be required at Locks and Dam No. 26 to implement this policy. The exact number of switchboats would depend on the length of queues and the percentage of tows requiring assistance.

The Industrial Canal Lock in New Orleans has had an operating rule which requires that the second half of a split tow move to the end of a waiting line. As a result, the towing industry pays for the use of an extra towboat to carry through the front half of a split tow at the same time.

(k) Guide Wall Extension
with an N-Up/N-Down
Policy

At some locks (such as Gallipolis) there could be some specific disadvantages, in terms of safety and industry desires, to reassembling barges outside the lock chamber, especially in the lower pool. Reassembling in a downstream mooring area could be hazardous because of the required tow maneuvers. Tows usually approach a moored cut when heading upstream. Since they will be headed downstream upon exit, each tow would have to turn 180 degrees in midstream. They would then approach the moored cut from downstream, recouple, and execute another 180 degree turn with the full tow.

An alternative to reassembling in the downstream approach is to provide an extended guide wall for reassembling (the landward guide wall or the guard wall between the main and auxiliary chamber could also be extended). This would probably cause interference with traffic during construction.

The effective capacity of a lock with extended guide walls in an approach would be about the same as employing

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a switchboat as long as a N-up/N-down procedure is fol-
lowed and haulage equipment is provided. In order to
achieve the same capacity with guide wall extension, the
last of a series of one-directional lockages should be a
single lockage in order to minimize delay to the tow
approaching from the opposite direction.

The guide wall extension should be long enough for an
entire tow to moor along the wall and clear the miter
gates and the filling and emptying system outlets. Delong
Piers, a floating boom or a concrete cap on sheet pile
cells could be used in lieu of a conventional concrete
wall.

Extension of the landward guard wall would probably
cause less interference to traffic during construction
than extension of the riverward guide wall. Where an
auxiliary chamber is available extension of the guide wall
between the two chambers could reduce approach blockages.

In approaches which are already restricted, extending
the guide wall may not be feasible as maneuvering room may
be decreased.

(1)   Ready-To-Serve
      Policy

The Ready-to-Serve operating policy prohibits the
break and remake of tows within or in the vicinity if a
lock chamber. Each separate cut of a large tow is assumed
to lock immediately following one another and is consid-
ered to be independently powered. The tow would be re-
quired to appear at an initial point for lockage some
distance from the lock, prepared to move through without
further changes in tow configuration. Tows appearing at
that point would be denied waiting line position if they
were not able to move through the lock without splitting
the tow, rearranging barges, or other time-consuming
modifications prior to entry into the lock itself. This
policy would require several switchboats at the lock at
all times to assist in the locking operations. Mooring
facilities would also be required.

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A method was developed in Element K1 to determine the applicability and effectiveness of this measure given site specific information.

The number of switchboats required would be reduced if knockout and setover type lockages were allowed to continue locking in an unrestricted manner. Towboats of tows waiting in line could be used in lieu of switchboats.

This operating procedure would provide the greatest benefits of any policy measure, preclude the use of some of the other policy measures and generally reduce the effectiveness of the N-up/N-down policy.

METHODS WHICH MAY FIND APPLICATION IN INCREASING LOCK CAPACITY

The following paragraphs discuss measures which could conceivably provide significant benefits by increasing lock capacity. However, these measures have never been implemented at existing locks in the United States for a variety of reasons. Several of the measures would require significant amount of basic research in order to prove their feasibility and effectiveness. For other measures, specifically those which are industry related, the full consequences of their employment would have to be investigated prior to proposing their implementation.

(a) Centralized and Automate Controls

Locks have been designed for many years with the idea that personnel should visually inspect the entrance, exits, and intake and outlet ports before operating gates or valves. As a result, controls in many places are located on opposite ends of 600 to 1200 feet of lock wall and sometimes one person is required to move from one end to the other on foot or with scooters to operate the lock. Considering modern control and industrial management processes, it may be worthwhile to consolidate all controls into one location and use closed-circuit TV monitors for visual scanning.

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Installation of closed circuit television covering the upper intake area and the lower discharge area with receivers in both the upper and lower control stands and position indicators that would depict the exact position of all the valves, would provide the lock operator with a continuous view of the discharge conditions and eliminate many trips to observe the area. In addition, the operator could commence an earlier opening of the discharge valves from the upper control stand.

Another improvement which offers considerable promise would be that of automatically controlled cycling of filling and operating sequences. Rather than have a variety of controls, modern industrial facilities today provide for automatic sensing and sequencing of steps in an operation. In this manner, large valves and heavy gates can be much more carefully and properly controlled than by manual operation. This might result in somewhat faster entry, chambering and exit times as well as less damage to lock components.

On the Welland Canal, by installation of higher efficiency valves, automating certain functions, centralized traffic control and alert operation of vessels, it was possible to gain one more lockage per day.

(b) Provide Separate
    Recreational Facilities

At a number of existing locks, lockages for recreational users are a substantial proportion of the total number of annual lockages. Projections for future recreational lockage demand vary from segment to segment but demand is expected, in general, to increase.

Conflicts between commercial waterway users and recreational waterway users have occurred at several locations, with resulting delays for both. Current lockage practices at most locks, limit the penalty imposed on recreational users.

The nature of the conflict between commercial and recreational users is subtle, however, and should be

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brought to light prior to discussing measures to eliminate it.

Recreational lock usage on most United States waterways primarily occurs during daylight hours, or weekends, during the summer (with weekday use at lower levels). This period of time, if devoted entirely to recreational uses, represents only about 4% of the time in a year and only decreases annual capacity by about the same amount. Monthly capacity during summer, however, would be reduced by about 14% as this period represents about 14% of the time in a month.

At the same time, commercial lock usage is also highly seasonal. If, during a month of heavy commercial congestion at a lock, traffic volume is 14% higher than in other months, then during the other months all the daylight hours, on weekends, can be devoted entirely to recreational users without increasing the average delay to commercial users above the average delay experienced during the most congested month.

In the report, "Analysis of Waterways System Capability," the period of current peak recreational lock usage was only found to correspond to the period of peak commercial lock usage on the Upper Mississippi, Columbia/Snake and Lower Tennessee Rivers. This situation could change in the future depending on both commodity flow and recreational demand forecasts.

At locations where congestion can become acute during some periods, consideration can be given to improving the efficiency of recreational usage to avoid occasional congestion. A practice which has gained acceptance at a number of locations is to restrict recreational lockages to scheduled hours. It has been found that if commercial users are made aware of the hours that the locks will be unavailable to them in order to service recreational users, the commercial users are able to schedule their cargo movements away from the locks during those hours. In order to insure the effectiveness of this measure, the

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report "Recreational Craft Locks Study, Selected Alternatives,"[9] recommended the following improvements to existing lock facilities on the Upper Mississippi River:

1. installation of a lockage information system which would give recreational boaters knowledge of the next scheduled small boat lockage (this would be in the form of signs, readable at distances up to 1000 feet and placed in strategic locations).

2. establishment of lockage waiting areas near each lock which would give recreational boaters a safe tie-up area while waiting for the next scheduled lockage.

If acute delays are anticipated due to recreational usage at locks which are operating at near capacity, other options should be considered. Eliminating the "maximum wait of three lockages" operating policy would have the probable effect of discouraging recreational usage. While this measure could be effective, the decision to implement it should be given careful consideration in light of the consequences. A measure which has been given increased consideration recently is the installation of separate recreational locking facilities. This measure would effectively eliminate congestion due to recreational usage.

Separate recreational facilities can be either locks or mechanical lifts. Of course, the dimensions can be significantly smaller than conventional locks to handle recreational craft either individually or in groups.

Several types of recreational locks and lifts have been given conceptual consideration ("Recreation Craft Locks Study, State II, Planning Report"[10]).

- a 110'x 360' conventional lock.

- a mobile floating lock.

- small scale steel lock.

- 25'-80' concrete and sheet pile lock.

- differential railway lift.

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- a steel tank on inclined lift.

- a steel tank lift crane.

- a mobile boat carrier.

- an inclined channel lift.

- an inclined plane lift.

These lock types are discussed further, however, to
date, no purely recreational lock has ever been con-
structed. Certainly, the technology required to build a
small conventional lock is well established. In Europe,
inclined plane and certain types of mechanical lift tech-
nologies are well established and have been used (see
Section III - Shiplifts).

(c) Impact Barriers

Impact barriers, to prevent vessels from striking lock
gates, are coming into wide usage in Europe but have not
been used in the United States except in the Soo locks and
at the St. Lawrence Seaway locks. To date, no completely
satisfactory design has been developed that is suitable
for tows having a sloping under surface on the bow end of
the leading barge. However, the increasing frequency of
accidents that damage lock gates is focusing attention on
impact barriers and satisfactory designs may soon be
developed.

In some cases, the use of impact barriers would reduce
the usable length of the chamber but would allow greater
entry speeds and much greater safety, in terms of reduced
risk of striking the lock gates.

(d)   Install
      Replaceable
      Fenders, Energy
      Absorbers and/
      or Rolling
      Fenders at
      Critical Sites
      on Lock Walls

From observations of damage at Lock and Dam No. 27 and
other locations, there may be an opportunity to improve
passage through a lock by providing replaceable fenders,
energy absorbers, and/or rolling fenders at critical
points on the lock walls. These items are often used
during mooring operations of ocean going ships.

The aims of these improvements would be to control the
alignment of vessels during entries and exits and to ex-
ternally apply a braking force on entering vessels thus
allowing greater entry speed or shorter entry time than if
the vessels had to rely solely on the braking capacity of
their propellers.

Considering the small clearances available at most
locks, particularly the clearance between the bow and the
miter gates, it may not be advisable to install systems
which would promote faster entry speeds (and thus increas-
ing the risk of striking the gates) unless some sort of
positive braking devices such as impact barriers are
routinely used.

(e)   Provide Waiting
      Areas Near Lock
      Gates

Enabling tows to tie-up close to the lock gates while
awaiting their turn to lock would conceivably provide
great time savings at locks by greatly reducing the time
of approach. The time of approach is generally a major
portion of the lock service time. In locks constructed in
canals or cutoffs where tows have been able to exchange
usage of the lock in the proximity of the lock, due to the
absence of currents, considerable reductions in service
time have been achieved.

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As described in Section III, most modern European
locks provide an offset waiting location close to the lock
entrance. The development of a similar type of offset
waiting area in the United States is hampered by a lack of
general knowledge as to the maneuverability of American
tows. It is not known whether or not comparably sized
United States and European tows have similar maneuvering
characteristics. American tows are typically much larger
than European tows and are therefore more difficult to
maneuver. Thus, a greater area would have to be reserved
for the lock approach. This may not be feasible at many
riverside locks.

The widespread use of bow steerers to increase the
maneuverability of tows would allow tows to leave a tie-up
area which is in close proximity to the lock gates and
maneuver into alignment with the lock entrance. Alter-
natively, mechanical devices such as a swinging arm from
the lock wall would grasp the tow and enable it to move
out into line with the lock entrance would be equally as
effective (to date, such devices have never been de-
signed). Such changes would eliminate the need for N-up/
N-down rules and permit two-way tow passage for each fill-
ing and emptying of a single lock. The effectiveness of
all other measures which reduce service time would be re-
duced with the implementation of this measure.

(f) Give Priority
     to Faster
     Locking Tows

In many instances, lockage times are long because the
tows are not operating very efficiently. In order to en-
courage tows to become more efficient during the lockage
process, rules could be developed for maneuverability such
that arrivals at an initial point for a given lock would
gain priority according to their ability to move rapidly
through the lock when waiting lines exist. Information on
the speed and maneuverability of the vessels would have to
be relayed to the lock operator so that he could then
choose the best sequence for lockage. (See (g), Estab-
lishment of More Responsive and Flexible Scheduling
Procedures.)

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Three areas of current technology if universally applied would have a significant effect on lock transit speeds:

1. increased tow speeds.

2. use of bow thruster.

3. use of universally adoptable coupler for joining barges.

All of these measures would require cooperation and coordination with the towing industry and are discussed in the section entitled "Industry Improvements."

A successful example of a change in rules which resulted in major benefits to the shipping industry is available in the Welland Canal Studies. In the Welland Canal, careful study revealed that when a waiting line formed for any reason, a slow ship would impede the progress of many ships if it were near the head of the line. When faster ships were allowed through the lock ahead of slower ships, the slower ship arrived at its destination at essentially the same time without delaying the faster vessels. The result then was a greater passage of tonnage per unit time through the entire system.

(g) Establishment
of More
Responsive and
Flexible
Scheduling
Procedures

A rigid scheduling procedure of a given number of tows and a given number down could result in inefficiencies in some instances. In this context, it may be possible to develop a responsive and flexible scheduling algorithm to establish which chamber a tow will use, the order of turn in which the tow will be served, and the lockage procedures which the tow must adhere to. The solutions provided by such a scheduling algorithm would vary depending on the length of the queue, the mix of lockage types and vessels desiring service, the origins and destinations of the tows, the elevations of the upper and lower pools, and

possibly a number of other factors. (See also (f), Give Priority to Faster Locking Tows, above.)

The situation at most locks is dynamic and substantial changes in traffic demands and queue length can occur in short time periods. Considerable benefits could therefore be obtained by establishing scheduling rules and lockage procedures which are flexible enough to be applied as the situation warrants. For example, during extremely light traffic, a first come, first served scheduling rule might be used. As traffic increases, a three-up, three-down scheduling rule might be instituted. When queues are longer (approximately 12 hours), procedures such as the use of helper boats to extract cuts might be instituted and setover rules might be put in effect. If the queue grows even longer (24 hours or more) more restrictive procedures might be used (e.g., a four-up, four-down scheduling rule, no decoupling of doubles within the lock, mandatory scheduling of tows for the auxiliary chamber). Such flexibility implies the use of some form of dynamic, or semi-real-time scheduling mechanism. Such a system, which could be queried and invoked several times a day, could then produce some-form of interactive scheduling and lockage procedures.

The flexible scheduling procedures can only be invoked if the lock staff has a tool available to it for arriving at a more optimal scheduling procedure for a given set of circumstances.

At locks with auxiliary chambers, a more responsive and flexible scheduling mechanism could increase the ability of both chambers to serve increased traffic. If tows could be selected from a waiting queue to effectively use the time available (when the approach channel is not blocked) to enter and exit from the lock and during the periods when the channel is blocked by operations in the main chamber, to break, chamber, remake, and perform other processing operations that do not require approach or exit of the tow through the channel, then the auxiliary chamber might possibly be utilized a higher percentage of the time.

Prior to the replacement of Lock and Dam 51 with Smithland Lock, a method was proposed to increase the

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capacity of Lock and Dam 51 by improved scheduling procedures. The study, "Use of Tow Sequencing Procedures to Increase the Capacity of Existing Lock Facilities,"[11] 1974 by L. Daggett (Waterways Experiment Station of the Army Corps of Engineers) developed a "real-time control system for use of a lock operator in determining the best order in which to schedule tows waiting for lockage." The study included providing a means of entering lockage data directly into a remote terminal to eliminate the need for keeping lock records by hand.

The computer program which was developed considers, rapidly, all the possible orders in which tows awaiting in queue at the lock could be locked. The order in which tows would be selected to lock would be based on the minimization of an objective function. The objective function could be selected from any one of the following:

       1. minimization of total waiting time (in minutes).

       2. minimization of total transit time (in minutes).

       3. minimization of the lockage rate of the barges of all tows in the queue under consideration (in minutes per barge).

       4. maximization of the lockage rate of the commodity tonnage of all tows in the queue under consideration (in tons per minute).

       5. minimization of total waiting costs (in dollars).

       6. minimization of total transit costs (in dollars).

The lock operator could choose from among the objective functions or could compare results. In addition, the program would provide the lock operators with the second and third best lockage orders.

The lock operator then would have the flexibility of choosing from among several possible lockage orders.

Finally, in order to not do away completely with the first-come-first-serve order, the program was developed to give limited priority to vessels which have been waiting the longest. The order of arrival is retained in the program as optimum until a minimum *improvement in the objective function* is obtained.

The program, as developed, took into account average service times and other lockage data similar to that which is now collected under the Performance Monitoring System (PMS). However, data on crew capability, weather conditions, visibility and river currents were not available to allow the program to be sensitive to these important factors.

The study concluded that use of a high-speed digital computer to sequence tows for lockage would increase the efficiency of lock operations because of the number of parameters which effect efficient usage. In particular, if it is desired to minimize total transit time or total transit costs much more information must be examined and analyzed in order to pick the optimum lockage sequence than if lock processing times are minimized. This is especially true if *consideration* is given to the value of the commodity moved.

The study suggested several rules of thumb that could be used at Lock 51 to schedule tows prior to the installation of a computer. These rules could possibly be modified for use at other sites. To minimize total waiting or transit time of tows:

     1. schedule tows according to lockage type in the following order: 1, single; 2, knockouts; 3, setovers; and 4, doubles.

     2. for like lockage types, schedule empty tows ahead of loaded tows.

     3. for tows of similar loading, schedule tows to minimize the number of long entries, i.e., sequential lockages, to the extent practical.

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To minimize minutes per barge or maximize tonnage per minute, ensure that tows are scheduled for short entry (sequential lockage of tows traveling in the same direction) according to the following priority list:

1. loaded tows traveling upstream chosen in the following order: 1, knockouts; 2, doubles; 3, setovers; and 4, singles.

2. empty doubles traveling upstream.

3. loaded doubles traveling downstream.

4. empty setovers or knockouts traveling upstream; loaded setovers or knockouts, downstream; empty doubles, downstream.

5. all others, i.e., empty singles, knockouts, and setover, traveling downstream; empty singles, upstream; and loaded singles, downstream.

PMS data which is now available for many locks, but which was not available when the program was developed, would greatly simplify the data collection efforts required to prepare the program for use. After the computer terminal is in operation, it could also be used to record PMS data. This would also allow the program to be updated occasionally. Unfortunately, many of the parameters to which the program was not sensitive, such as visibility, river currents, wind and crew capability could not be developed for incorporation without a considerable amount of effort. A considerable amount of work would also be necessary to make the program sensitive to commodity types. The program could also be used, after additional development, to improve lockage operations at locks with multi-chambers and at locks with a considerable amount of recreational traffic.

Once the program is developed, it and the computer terminal could be moved to another lock site for use if the original lock is replaced.

Consideration should also be given in tow scheduling to account for priorities for military, passenger, maintenance and other types of vessels.

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(h) Waterway
     Traffic
     Regulation

A great deal of speculation has been devoted to the
subject of traffic regulation. It is felt, by most, that
if the lock master has prior knowledge of the time of
arrival and the size and configuration of the vessel or
tow well in advance of the vessel's arrival at the lock,
then lock operations could be more efficiently undertaken
and traffic flow more evenly distributed. In this way,
the reduction in lock capacity induced by the randomness
of vessel arrivals could be lessened.

The terms traffic management and traffic control as
used in other transportation networks or in marine ship-
ping usually refers to activities required to fix the
instantaneous position of a vehicle in order to insure its
safe operation in areas of high congestion (reduce the
risk of collision). On inland waterways, however, traffic
management would most likely be associated with obtaining
general traffic information in order to optimize the uti-
lization of facilities and reduce delays.

A Vessel Traffic System, sometimes referred to as a
Vessel Traffic Management System (VTMS) is defined by the
United States Coast Guard as "An integrated system encom-
passing the variety of technologies, equipment and people
employed to coordinate vessel movements in or approaching
a port or waterway." In its simplest form, a VTMS com-
prises no more than a system or rules and procedures con-
cerning the use of the waterway (for example, a first-
come-first-serve policy). In somewhat more critical
researches, the VTMS could comprise a communication system
(two-way radio) in order to report vessel movements,
forestalling congestion at bottlenecks. The verbal
reporting can include useful hydraulic and meteorological
information.

In more complex situations, the traffic manager could
have a radar screen to assess the traffic pattern. There
are three possible levels of radar utilization. At the
first level, the radar observer can communicate with the
vessels he observes on the radar screen. At the second
level, he is assisted by a limited information processing

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system which enables him to better plan and control traffic. At the third, most sophisticated level, a link is set up between the information processing system and the radar unit making vessel identification and continuous tracking possible and allowing the waterway capacity to be further expanded. The most up-to-date Air Traffic Control Systems are based on the principles of the third level system.

With the exception of busy maritime ports and coastal ports which serve for the transhipment of cargo to the inland fleet, it is very unlikely that a system as complex as the third level system would ever become necessary.

At the present time, inland waterway vessel traffic systems are limited to established navigation procedures and radio communications at locks. Under the present system, the lock master directs traffic entering and leaving the lock area by radio in order to insure timely and safe passage by all vessels. With the present system, the lock master can also advise the vessel pilots of conditions at the lock and collect lockage information (PMS data).

The present system, however, is limited by the current procedure which does not require the vessels to contact the lock master prior to arrival at approach point (within several hundred feet of the lock). Indeed, the power of the present communication system would not allow direct radio contact over appreciably longer distances. This, of course, limits the lock master's ability to plan and direct lockages for efficient utilization beyond those vessels waiting at the approach points.

The potential for increased traffic control within the lock operator's normal range of influence was discussed in the previous sectio. This section deals with more powerful systems for multi-reach control and traffic coordination.

An example of a location where traffic congestion has resulted in investigations into vessel traffic management systems is Dardrecht in the Netherlands. In the vicinity

of this Dutch town, which is at the junction of several
important rivers, improvement of the waterway by widening
and relieving one-way reaches (such as bridges) was found
to be infeasible because of local land development. A
traffic management system has been planned for this town.
The system planned will be similar to other systems cur-
rently in use for Dutch maritime ports. The system will
comprise aspects of a traffic control center, a radar
system to monitor the position of vessels and an informa-
tion system to monitor tide levels and currents. In this
respect, it is very much like a level two system. The
traffic control center will serve the following purposes:

     1. to coordinate water-borne patrol services and
to provide information on the shipping situation, water
levels, currents, visibility, weather, etc.

     2. to regulate and guide shipping in cooperation
with patrol vessels on the Old Meuse, the Dortsche Kil,
Noord and Merwede waterways, particularly during launch-
ings, construction work on the river, special transport,
sailing competitions, disasters, etc.

     3. to regulate the negotiation of bridges near
Dardrecht and to provide information on waiting times
which could lead to a different route being chosen to save
time.

     4. to record dangerous goods being transported
so that adequate steps can be taken if a disaster occurs.

To perform these functions, the center will be fitted
with VHF equipment with channels for communication with
maritime and inland shipping and service craft. Commun-
ication with the Rotterdam Harbor Coordination Center and
other traffic centers in the area will be conducted by
telephone and telex. The hydrological information re-
quired will be obtained from nine stations; six providing
water levels and three providing current speeds in the
area of operation.

On the Humber Waterway in England, a vessel traffic
management system has been proposed which is intended not
only to facilitate traffic movement and increase safety
but also to greatly reduce operating costs. The system
which was the culmination of research efforts is known as

AARCLAB (Automation and Remote Control of Locks and Bridges). The purpose of ARCLAB is to transfer the control of the 31 locks and 18 bridges on the waterway to three distant control centers by telemetry and to provide visual surveillance of the site by closed circuit television systems associated with an entirely new system of barge detection. In addition to operating and controlling locks and bridges, the three centers would monitor the flow of traffic and provide surveillance of the automated water control system. A silicon diode tube television camera was proposed to provide adequate vision during poor weather conditions and with limited floodlighting. Vessels entering a lock or bridge area would be detected by using ultra sonic beams underwater which have been found to be up to 100% accurate at distances up to 100 meters. The detectors would activated an alarm at the control center and the television camera facing the approaching craft. Under the ARCLAB system, water levels are monitored throughout the system and at all times the operator is provided with an up-to-date picture of the complete system showing the position of lock gates, sluices, bridges, traffic lights and vessel movements. Each vessel entering the system is provided with a code. When the code is read at the television monitor, it can be entered prior to commencement of an operation and a data-logger automatically prints out the date, time, lock name, craft code and direction of travel. Commodities and destinations could also be printed. Using the ARCLAB system it is anticipated that a marked improvement in vessel transit times will be possible as the controller will be able to anticipate vessel movements.

In the United States, the above technologies could have limited application. However, there are very few locations which could ever be expected to be congested enough to require complete radar control and, in general, distances between locks and constraint areas are too great to allow significant consolidation of operations.

In 1974 the study, "A Feasibility Study of Real Time Performance Monitoring Systems for the Inland Waterways of the United States,"[12] was performed for the Corps of Engineers under the auspices of the Inland Navigation Systems Analysis (INSA) Program.

The study investigated four Vessel Traffic Management Systems which would have additional benefits beyond the existing Performance Monitoring System (PMS) by decreasing the time required to collect and distribute data and increasing its range of users.

The value of the existing PMS is primarily for purposes of long term planning and operations management. As such, it can be used to evaluate and improve lock performance; provide input for the design and scheduling of new lock construction; predict trends in traffic characteristics; and provide valuable information on lock and navigation operations for management.

However, a system which could provide information faster could be more widely used and provide additional benefits. Table IV-1 presents a time frame in which information must be available for several uses in order to aid in decision making.

A semi-automatic data system collection alternative was evaluated but could not be justified due to the cost for equipment. Under this system, PMS data logs would be put into machine readable form at the locks and then sent directly to the Division computer.

A local traffic and waterway status alternative would collect data similar to PMS data; however, the data would be entered at the lock and immediately transmitted to a minicomputer. There would be approximately 25 minicomputers needed to accommodate the entire inland waterway system. Each computer would contain information such as the number of tows waiting at each lock, current (and projected) delays, available channel depth, weather and similar data. This information could be accessed by any authorized user, whereby towing companies could improve their scheduling or resources, increase safety on the waterways being monitored, and provide a better waterway status for those who must maintain and patrol the waterway. These data and information would be continuously available by standard dial-up telephones. Because the 25 minicomputers would not be interconnected, however, each would have to be queried independently, reducing its potential for many users.

Table IV-1

Real-Time Information Needs/Time Requirements

Users/Type of Information	T
Towboat Operators Navigation Information	Hours
United States Coast Guard	Hours

Lockmasters
  Locking Priority Routines
  Dependent on Information from
  Outside His Own Lock Area
	1 to 4 Hours

Tow Company Dispatcher
  Traffic and Waterways Status
  Information
	4 to 20 Hours

Corps of Engineers and Tow Company
  Management Long Term Planning
  and Operations Analysis
	Days to Months

SOURCE: A Feasibility Study of Real-Time Performance
Monitoring Systems for the Inland Waterways,
Corps of Engineers

A complete traffic and waterway status alternative
would include the capabilities of the local systems plus
have the ability to report on delay points other than
locks and report on traffic and navigation conditions at
major areas of high tow concentration other than locks.
These data would be collected either manually or mechan-
ically and transmitted to a central minicomputer. The
total data base would be available to tow operators and
others by telephone dial-up. Absolute reliability of the
system would be assured by back-up equipment.

Benefits would be the same as for the local system
except in greater magnitude because of the augmented data
base and the fact that total waterways data would be
available to all tow operators as well as other users.

A global control system would control all entities of the waterways based on information obtained from the entire waterways. The system to collect and display these data would be highly sophisticated as would the policy for controlling the waterways. In general, a system for a global control would include the benefits of improved data collection, local control, waterways operations data availability as well as the benefit of global control. However, it is possible that global control may limit or completely eliminate local control and tow company dispatcher options; this could reduce the level of benefits.

Of the above four systems investigated, the complete traffic and waterway status alternative was found to be the most cost effective when benefits of increased productivity, reduced operating costs, increased safety, increased reliability and increased convenience were examined. A pilot study to further examine the feasibility and effectiveness of this alternative was recommended but to date has not been undertaken.

(i)   Industry
      Improvements

There are a number of areas in which the towing industry could improve the efficiency with which it utilizes lockage facilities. It should be recognized, however, that the towing industry generally adopts measures which can improve their ability to transport cargo whenever such measures can be economically justified. The following paragraphs discuss measures, therefore, which in general require further study of development prior to being judged feasible for implementation.

The greatest potential gains in overall improved waterway capacity as a result of industry improvements is not restricted to reducing lockage time but would appear to be in the areas of improving tow configurations, reducing empty backhaul and evening out seasonal effects. These are areas in which the Corps of Engineers, as operators of the national system of locks, has traditionally exercised little control. While some potential measures directed towards these goals are discussed in the following paragraphs, a great deal of potential for additional developments exist.

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1. Increase Tow Powering. There have been various reports of tows, especially very large or underpowered one having considerable difficulty in executing necessary locking maneuvers. Large tows operating with small clearances in lock areas require very precise steering, and most tows are difficult to control if lock approaches and exits are complicated by cross currents, wind, or heavy traffic. Increased power is generally synonymous with increased speed and maneuverability, and increased fuel usage.

Towboat powering requirements are based on the optimization of a number of factors including:

> (a) adequate power to safely navigate under existing channel conditions (between locks).

> (b) adequate power to safely approach locks.

> (c) minimizing transit time.

> (d) minimizing capital and maintenance expenses (including fuel).

While it would be desirable to set minimum horsepower requirements for tows approaching a lock in order to reduce approach times (values of 200-250 hp per barge or per 1500 tons of cargo have been suggested), the effect of the change on transportation costs should be considered. Additional studies would have to be underaken to determine the time savings attainable at the lock by implementing this measure and the associated cost to the industry in terms of changes in the above factors.

2. Use of Bow Thrusters. There are two basic types of bow thrusters (or bow steerers) in use. Small, portable, low powered bow thrusters are attached to the bows of vessels for use in reservoirs and lakes, primarily to counteract wind effects. Propeller or jet powered bow thrusters can be installed on a small barge unit and then lashed to the front of tows. This latter device would probably be most applicable to inland waterways (where strong currents are prevalent).

Because bow thrusters increase the maneuverability of the tow, their use could substantially reduce the time required for the tow to become aligned with the

lock (approach time). As noted previously, it may even be possible to allow tows to wait in an offset area near the lock gates for exchange of the lock.

To date, bow thruster tests have only been conducted in still waters. While propellor type bow thrusters have been employed sucessfully to improve the steerage of downbound tows on the lower Mississippi River, the maneuverability of tows equipped with bow thrusters in open river conditions is not documented.

In any event, a tow equipped with a bow thruster should be capable of exchanging use of a lock closer to the locks becausek of increased mobility. A disadvantage of the use of bow thrusters is that the units, when attached to the front of the tow reduce the usable dimensions of the lock thus reducing capacity. This may offset the advantage gained by a faster approach. The widespread use of the bow thrusters could possible increase capacity but additional work would be required to establish the magnitude of time savings during the approach and possible loss of usable cargo dimensions.

While adoption of bow thrusters would constitute a change in industry operation, additional benefits would be gained by the industry, specifically increased safety when navigating under adverse weather conditions, in highly congested areas, in restricted channels and during docking and landing operations.

Establishing a policy of giving priority to faster locking tows might help to encourage the industry to adopt the usage of bow thrusters.

Alternatively, bow thrusters could be made available at congested locks for use by industry during the lockage procedure.

3. Universally Adaptable Coupler for Joining Barges. At the present time, mooring and barge couplings are made by traditionally effective but slow methods which are quite time-consuming when tows must be disassembled and reassembled. The development of a simple, quick-operating, and universally adaptable coupler for joining barges could save a considerable amount of time in breaking and remaking tows for multiple cut lockayes (where a few minutes saved by each tow would greatly increase lock capacity). Mounted on all sides of all barges, such

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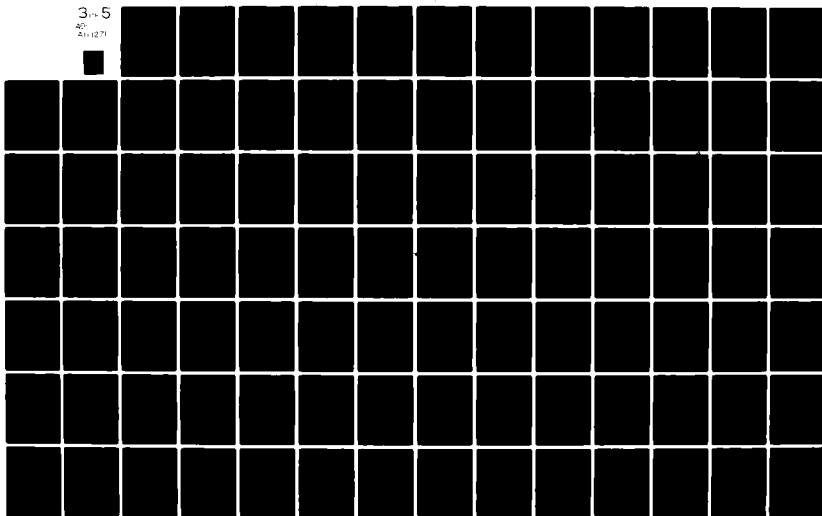
devices could prove vastly more economical than traditional rigging and lashings. Alternatively, hand winches could be employed which can be operated much faster than the ratchet and cable method and allow the outside lines of the tow to be secured, permitting the tow to clear the lock while deckhands are securing the remaining cables.

The coupler, if adopted, would have to be retrofitted on all barges and would have to be capable of working on all barge types and in the full range of barge drafts (i.e., capable of attaching empty barges to fully loaded barges). It would be difficult to design a coupler that would work under these conditions and no proven effective designs have been proposed.

4. Additional Improvements. In the area of long term industry planning, many types of hardware changes are possible. Special consideration of hydraulic and aerodynamic characteristics of barges may result in lower drag forces on barges and improved handling under rough current and wind conditions. In applications where the one-way movement of empty barges is unavoidable, it may be possible to stack empty barges one on top of another and cut the required area of the tow in half. Although this would require complex handling equipment, hydraulic drag would be reduced, and double lockages could be eliminated at most places on the return trip of tows which required double lockages in their loaded configuration.

A towboat system that has been used in Europe and which might find favorable application in this country is the "automotive coupled unit." In this system, each tow is propelled by two independent towboats whose controls can, however, be coupled and operated by a single pilot in the master towboat. This system is somewhat more maneuverable than a single towboat system because of the spacing between the two boats which push side by side at the sterm of the tow. The biggest advantage in such a combination though would be the convenience of having tow towboats available for switching operations. The tow could normally be operated by a single pilot who could be assigned by special pilots permanently stationed at locks and ports. When double lockages are necessary, the tow could be split up and remade far enough from the lock to avoid any traffic interference and the two independent parts of the tow could pass through the lock in the same manner as any single-locked tow. Thus the need for a local switchboat at each location would be eliminated and

the full capability of each towboat could be utilized at all times.

There is also the opportunity for the industry to improve itself through closer cooperation of individual operators. This could include assistance in the determination of the maximum practical size of tows to be used on the waterways as well as regulation of such size once it is determined. The Corps of Engineers could also take an active part in the regulation of tow sizes.

Another important gain of this type could be achieved through more cooperative scheduling and sharing of equipment through greater cooperation among different operators. The opportunity for this is evidenced by the two-way empty barge traffic noted on some reaches of the waterways system. Where empty barges are similar in these instances, there appears to be no reason other than lack of willingness to share equipment that prevents the movement of only full barges of that type in at least one direction. The savings in wasted energy as well as the resultant share of gains to overall system efficiency might offset any associated increase in management costs. Along with this general idea goes the possibility that a sort of industry-wide clearinghouse could be established to keep track of waterways equipment.

Shipper ownership of barges, especially dedicated equipment, sometimes restricts their full time utilization, but this may be resolved through cooperative agreements. Another concept aimed at reducing empty barge traffic would be the development of hybrid equipment types where the nature of the cargo permits. As an example, the adaptation of some sort of inflatable bladder would allow a barge to transport liquids within the bladder on trips in one direction while hauling general dry cargo otherwise on the return trip.

An extension to this type of operation could require tows to break out barges and combine them with other tows in order to fill the lock chamber. To obtain any measurable benefit from this procedure, tows of the proper configuration must be present at the same time with enough time available to them prior to lockage to perform the reassembling necessary. Factors such as legal responsibility and insurance liability for the vessels and cargo may make implementing such a plan difficult.

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V - CHANNELS

The basis for any scientific or engineering analysis of the design of waterways and waterborne vehicles is the examination of the forces and moments acting on the vessels. The hydrostatic force and moments acting on tows, that is, the total buoyancy and the longitudinal and transverse distributions of buoyancy, are responsible for draft, trim, heel, and structural loads. Tow-channel interactions are largely governed by hydrodynamic forces and moments.

The forces acting in the longitudinal direction of moving tows are thrust, in the direction of motion, and drag, in the opposite direction. Thrust, the result of propeller action in the water, is a function of the engine power, type of propulsion system, hull design, and the channel dimensions. Hydrodynamic drag can be attributed to three phenomena; (1) the friction of the water flow past the wetted surface of the hull, (2) the energy required to support the wave system created by the tow and carried along with it, including changes in the surface level caused by the passage of the tow in restricted channels, and (3) the edies caused by separation of flow from the hull at points where the underwater shape of the tow changes abruptly, known as form drag. A small amount of additional drag is due to the friction and form drag of the air flow past the superstructure of the tow. Drag depends on the size and configuration of the tow, including the type of barges used, the channel dimensions, and the speed of the tow.

Hydrodynamic moments which cause tows to yaw (the pitch and roll of tows is minimal because of the great stability inherent in large transverse and longitudinal second moments of waterplane area of tows) result from asymmetric pressure distributions along the tow caused by local water and wind flow velocities. The magnitude and centroid of the moment depend on the number and type of rudders, and rudder angle, the strength and direction of the wind, current, and waves, the speed of the tow, and the channel dimensions.

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Channel geometry has a strong impact on the forces and moments acting on tows, and is therefore the subject of ongoing research. The maneuvering of vessels in restricted channels is often modeled as a double feedback loop problem involving the control process in one loop and the vessel-channel hydrodynamic interaction in the other. The later process is also referred to as the geometry effect loop. The complexity of these hydrodynamic interactions is such that much of what is known and presented here results from experiments, observations, and simplified theoretical analysis, rather than full theoretical treatments; the simultaneous partial differential equations of hydrodynamics cannot be solved in closed form except for cases of very simple geometries, flows, and boundary conditions. The vast computational power of the digital computer has made possible numerical solutions of more difficult problems, using techniques such as finite differences and finite elements; there are many published works on the mathematical modeling of vessel behavior in confined waters.[13] Experience has shown that these models can satisfactorily predict the performance of vessels in open water, even if depth is restricted, but their validity in restricted waterways is limited. Difficulties arise because of the need to incorporate the effects of nonuniform currents on the flow forces and the need to calculate control and flow forces as a function of the position and speed of the vessel with respect to the bottom and banks of the channel. Knowledge of these effects is rather limited and as a result these interactions are difficult to represent in mathematical terms. The complexities inherent in mathematical as well as physical models of tow maneuverability and the techniques currently in use to resolve these difficulties are discussed by Huval and Pickering.[14]

Many specific tow-channel hydrodynamic interactions are discussed from the point of view of channel design.

The important dimensions of channels as they affect the passage of vessels are depth, width, cross sectional area, and the radius of curvature at bends. A given tow size implies certain required minimum values for each of these dimensions individually, largely because of safety consideratons. In addition, the dimensions all interact through the speed of the tow, that is, once the minimum channel requirements for the size of the tow are met,

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desired speeds and degrees of restriction on navigation can be achieved with different combinations of values of the channel dimensions, provided that minimum requirements are not violated.

Most of the channel design standards presented here are intended to provide unrestricted navigation. In many cases, it may not be economic to do so, as the cost of constructing and maintaining a first-class waterway may not be offset by benefits of reduced constraints on navigation. Hence, some reaches on existing waterways do not meet these standards as applied to the maximum tow size in common use on that waterway. Corps design standards are based on a given set of conditions, tow, size, and horsepower; private towing companies may find it economic to operate larger tows in less favorable conditions, trading off the increased difficulty of navigation for the economics of scale of larger tows. Another factor is the frequency of restricted reaches; a waterway which provides excellent navigation conditions over 95% of its length can hardly be considered restricted because of very few difficult reaches. A further discussion of the relationships between channel dimensions, tow size, degree of constraint on navigation, and frequency of restricted reaches and a comparison of the existing waterway system to design standards for unrestricted navigation may be found in the Report "Analysis of Waterways System Capability."

The subsequent subsections consider first the minimum requirements of each dimension individually, and then the interactions between them.

Coastal approach channels are similar in some respects but are vastly different in others. Required depth, width, and radius in coastal channel can be analyzed in much the same way as in inland waterways, but the hydrodynamic interactions of tidal and estuarine flows and ocean waves can cause navigation difficulties not encountered inland. One example is the entrance to the ports at the mouth of the Columbia River. Under adverse circumstances, this can be the worst harbor approach in the United States, and it is not uncommon for pilots to wait several hours until conditions improve. Dr. Lee Harris of CERC hypothesizes an explanation: The ebb tide in the Lower Columbia acts as a classical hydrodynamic

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jet; the velocity in the jet is highest in the center of
the channel. This flow, carrying substantial energy,
interacts with incoming long crested waves, not merely
diffracting them, but transmitting some of the energy of
the jet into increased wave height. There are reports of
wave heights in the river mouth twice those in the open
sea beyond the range of the jet. Accordingly, waves must
be much steeper, as well. Dr. Harris is currently col-
lecting and reviewing preliminary data from the area which
so far appears to corroborate his hypothesis. It is be-
lieved that this effect of the interaction of tidal flow
and oncoming waves, while most prominent in the Columbia,
may be significant at many other coastal ports.

CHANNEL DEPTH

The limited depth of a channel imposes a limiting
speed on tows, increases resistance, reduces maneuver-
ability, can limit the capacity of the waterway, and can
increase transportation costs. This section discusses the
basis of the selection of the appropriate depth of
channels.

The analysis of required depth in coastal approach
channels is identical to that of inland waterways;[15] the
components of required depth break down in exactly the
same way.

The design channel depth is a function of several com-
ponents. The design depth, D, is given by:

$$D = f(draft + squat + trim + motion + tide + water\ density + clearance)$$

(a) Draft

The draft of the design vessel for a new waterway will
be governed either by economic projections or by the
fleets operating on continuous existing waterways. Exten-
sions of existing waterway networks would very likely be
designed to handle tahe same vessels currently operating
on the network. A new waterway on which the traffic was
expected to be relatively independent of existing arteries
would require economic analysis to select an appropriate

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design vessel or fleet. There are usually economies of scale associated with larger vessels and tows which would be balanced against the increased initial and maintenance costs of the bigger channels needed. In most cases, the appropriate design for a domestic waterway will consist of a mix of the standard vessels currently in use in the United States. The design draft for the waterway will, of course be the draft of the deepest vessel in the fleet.

(b) Squat and Trim

Squat and trim are, respectively, dynamic and static variations in the draft of vessels. Vessels are frequently designed or loaded so that the draft at the bow is different from the draft of the stern. If only one number is cited for draft, it is generally the average draft amidships. Thus, if the vessel is trimmed by the stern or by the bow, it actually draws more water than the nominal draft indicates.

Squat or sinkage, as it if often called in European scientific literature, is a dynamic phenomenon occurring in waterways with limited cross sections. The passage of vessels lowers the surface of the water in the vicinity of the Bernoulli's laws for fluid flow. The draft of the vessel remains the same, but it is pulled closer to the bottom. The amount of squat increases with the speed of the vessel and inversely with the size of the channel cross section. The amount of squat also depends on the position of the vessel in the channel, the vessel configuration, and the static clearance over the bottom. These two parameters thus limit the speed of tows to that speed above which the vessel will touch bottom. Squat and the required tow power are plotted against speed in Figure V-A. The effect of depth is shown by parametric curves. There are many methods available for calculating sinkage, but often a rule-of-thumb prevails in the design of waterways. The South Atlantic Division recommends allowances for inland harbors and approaches of one foot for trim and one foot for squat. This practice is generally followed on canalized and free-flowing rivers, as well, in the United States.

Canals generally have smaller cross sections than canalized or free-flowing river channels, and should have

Figure V-A

Change of Water Level and Power vs. Tow Speed
(after Kohn[16])
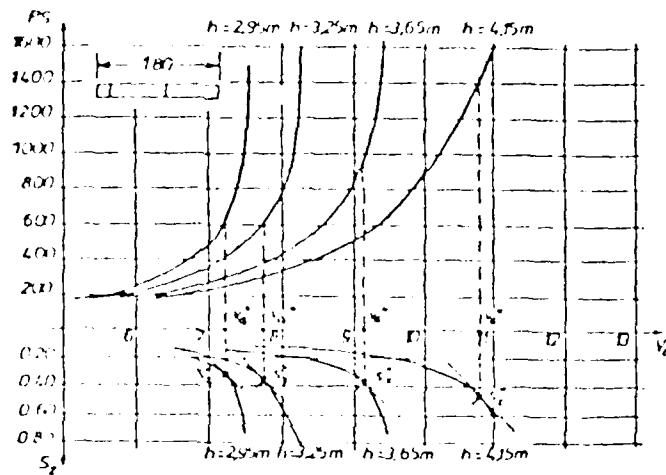
P.S. = Towboat Horsepower (metric)
S_z = Squat, meters

V_g = Tow Speed, Km/hr

h = Channel Depth, m

a higher allowance for squat, if vessel speed is to be maintained.

(c) Motion

Waterborne vehicles have six degrees of freedom for motion - three translations and three rotations about orthogonal axes. Two of these, heave and pitch, can affect the required depth of a waterway. The effect of roll on required depth is usually not significant. Vessels oscillate along these degrees of freedom under the influence of wave forces. Motions are therefore not usually an important consideration in inland waterways, except at points in the vicinity of a coastal area or areas affected by water releases from reservoirs. The allowance for wave motion depends on the severity of the waves. Ports on the Gulf of Mexico have smaller allowances (about two feet) than on the Atlantic or Pacific. A rule-of-thumb in common use is the provision of extra depth equal to one-third of the design wave height, assuming that wave length is smaller than length of hull.

(d) Tides

Estuarines are defined to be the areas where fresh and salt water mix, and are thus often subject to the effects of tides. Waterways in these areas are usually designed to be navigable at the lowest normal tides. In some tidal areas, sufficient depth is not maintained at low tide, and deeply laden vessels must either lighter or wait for the tide to turn. Whether or not to maintain navigable depth at low tide is an economic decision based on the trade off between the cost of a deeper channel and the costs of vessel delay, lightering, or the restriction of the waterway to shallow draft vessels.

(e) Water Density

Inland waterways contiguous with coastal ports often carry marine vessels. Fresh water is less dense than salt water, and Archimedes' Law requires that marine vessels float at a deeper draft in fresh water. Typically, an extra foot of depth in fresh water is provided as an adequate margin.

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(f) Clearance

Clearance, as it is used here, represents the distance between the bottom of the channel and the lowest point on the hull of vessels navigating the channel. Some of all of the allowances for sinkage, trim, motions, tide, and water density are often included in the measure of clearance used in the literature, but since all of those have been accounted for explicitly in previous paragraphs, this section is restricted to a discussion of the narrowly-defined clearance.

The minimum amount of clearance is determined by safety considerations; factors such as vessels moving at speeds which will cause sinkage in excess of the margin provided or the possibility of more severe motions than expected should be considered.

The type of bottom enters into the safety margin as well. More damage to vessels would be expected from contact with rock than silt, for example, and thus the clearance over hard bottoms is often greater than that over soft bottoms.

Another factor entering into the design clearance is the phenomenon of shallow channel limiting speed. The speed of displacement vessels in a channel of finite depth cannot exceed the propagation speed of long waves in that channel. This limiting speed is:

$$V_1 = K\sqrt{gh}$$

where V_1 is the limiting speed, g is the acceleration due to gravity, h is the depth of the channel, and K is a coefficient related to the cross section of the channel. K is equal to one in unlimited waterways, e.g., the ocean, and decreases with cross sectional area. In practice, the drag on vessels increases rapidly as speed nears the limiting speed and it is rarely economic for vessels to exceed 70% of the limiting speed. Channel clearance must be sufficient to allow a depth which will permit the design fleet to attain their expected speed.

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Any additional depth which is provided beyond the sum
of the factors above is discretionary; it is the result of
an economic decision balancing reduced transportation
costs against the increased construction and maintenance
costs of a deeper channel.

Reductions in transportation cost arise partly from
the decrease in hydrodynamic drag associated with a deeper
channel. The speed of vessels is increased at a constant
rate of fuel consumption in a deeper channel which leads
to a shorter transit time. The shorter transit time
implies a lower cost to shippers of inventory in transit
and more trips per year to the vessel operators, resulting
in a higher utilization rate of their capital equipment.
If speed is held constant, fuel consumption is decreased.

The speed of tows as a function of channel dimensions,
including depth is discussed in the Report "Analysis of
Waterways System Capability," based on the methodology of
Hochstein. Fuel consumption, tow speed, and channel depth
are also examined by Marbury in Least-Energy Operation of
River Shipping, Chesapeake Section, S.N.A.M.E., September
1977.

These formulations satisfactorily describe the spee
of typical tows in unconstrained channels, (as distinct
from channels restricted by inadequate dimensions, whic.
are considered) but cannot account directly for the
effects of various constraints on navigation such as one
way reaches, narrow bridge spans, landings and marianas,
and bends which must be flanked. One way to address the
problems would be empirical research perhaps utilizing P
data, aimed at determining coefficients to be applied to
speeds calculated with the methods above. The effect of
constraints on navigation on transit time is covered in
more detail in the Report "Analysis of Waterways System
Capability."

Another deficiency of the currently available analyti
cal models of tow speed is that they deal only with typi-
cal tow configurations. Research is needed to further
specify analytically the speed of tows with some or all
integrated barges or atypical configurations. There are
vast number of studies of tow resistance which have dealt

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with various configurations, but none have so far integrated towboat thrust and tow drag and made the leap to speed.

The Waterways Experimental Station is currently considering future research on the effects of channel depth on resistance and maneuverability. These problems will probably be approached by WES using both mathematical and physical models. The state-of-the-art in physical modeling of shallow draft hydrodynamics is currently further advanced than that of theortetical analysis, which will be a consideration in future research plans. The dual path combining both types of study is strongly supported by WES.

Alternatively, tow operators can load their barges beyond the design draft in order to take advantage of a deeper channel. This represents an immediate increase in the productivity of the tow, and is very common in practice. The GREAT I study presents an example of the economics involved.

Based on analysis made in the Report "Analysis of Waterways System Capability," it was concluded that the greatest savings from increased channel depth and width comes from increased utilization of barge draft, and tow size, with much smaller savings associated with increased tow speed in a larger channel. Once the controlling channel dimensions are sufficient to form as heavy tows as possible, the cost, savings of additional channel depth and width is minimal, as tow speed is increased (or fuel consumption decreased) very little. At the same time, initial and maintenance costs for channel enlargement increase very rapidly. Hence the general conclusion is that even with high fuel costs, it is difficult to anticipate that channel enlargement can be justified by increased tow speed or reduced fuel consumption only.

Tow operators check with the Corps regularly on the expected available depth, which varies with the water flow. They then load their barges to a draft which provides them with whatever clearance they feel is necessary. This clearance is sometimes as little as six inches, but is usually more if the bottom is hard or if the barges contain hazardous cargoes.

On the cost side, a paper by Hochstein[17] discusses the cost of maintaining channel depth by dredging, and graphically illustrates the trade-off between transportation cost and maintenance cost for channels of varying depth.

(g) Design
Standards

Ideally, the determination of design depth should be split into two parts. First, the components of the design depth which are independent of other channel dimensions should be calculated. These are the design draft and the allowances for expected trim, motions, tides, water density changes and clearance which together specify the lower bound of the design depth. Next, the sinkage component of depth which interacts with the other channel dimensions, should be estimated simultaneously with the design values of the other dimensions, bearing in mind the design speed for the water. Dand and White "Design of Navigation Canals,"[18] describes a methodology for this process.

In practice, the allowances for trim, motions, tides, and water density changes are usually zero on inland waterways. Depth is determined by the draft and sinkage and maneuverability behavior of the design fleet. Experiments have shown that the depth required to accommodate acceptable squat and maneuverability is proportional to draft. Therefore, channel depth requirements are most often stated as multiples of the draft of the design vessel.

Several European experimenters and planners recommend depths of approximate 1.5 times the draft of the design vessel. These are based on canals and vessels with cross sectional area ratios around six to eight and vessel speeds of six to eight mph. Koster[19] recommends deeper depths if overtaking situations with an oncoming vessel (three lanes of traffic) are expected.

Inland waterways in the United States tend to have much larger cross sections than European waterways, and so less attention seems to have been paid in the literature

to the selection of design depth. This may also be due to the fact that most of the major commercial river arteries in the United States have nine food depths, which strongly influences the design barges. A rule-of-thumb referred to by personnel at the Corps Waterways Experimental Station (WES) suggest that for proper steering, a design depth of two to three times the propellor diameter of the towboat. If the propellor diameter is assumed to be 80 percent of the draft of the towboat, a design depth of 1.6 to 2.4 times the draft of the towboat results. The assumption of a towboat draft ot two-thirds of the draft of the tow yields a design depth standard roughly in the neighborhood of the European standards. No blockage ratio or speed is cited with this estimate, which perhaps accounts for its wide range. As a minimum, WES personnel recommend that the allowance for sinkage and clearance be equal to at leas one-half the diameter of the towboat propeller which comes to about 2'-2.5'. As it was mentioned above, in practice, clearance can be as low as 0.5'-1.0'. The reason is that except in man-made canals, the minimum clearance actually appears along only a fraction of the waterway length. In freeflowing rivers it generally occurs on shoals at low flow stage and in canalized rivers it is significant only in the upper portions of the pools. As a result, the towing industry prefers to utilize fleet capacity and accept occasional reductions in speed and a slightly higher risk of grounding.

Personnel at the South Atlantic Division (SAD) use the following allowances to determine the depth of harbors: one foot for fresh water, two feet for waves, and two feet for clearance. The wave allowance is four feet in San Juan, and higher still in Atlantic and Pacific ports. According to NCD personnel, 27 foot projects in the Great Lakes allow two feet clearance as well.

As it was mentioned above, the allowance for sinkage depends on the cross sectional area of the channel and the speed of the vessels. The importance of design speed to design depth is illustrated by a formula in Appendix D of Koster[20], which relates empirically water depth and the fraction of full power actually developed in a restricted channel.

CHANNEL WIDTH

(a) Straight Reach

1. Inland Waterways. The width of a navigation
channel must include in addition to the width of the de-
sign vessels, clearances between vessels and the banks,
and between the vessels themselves, if two-way traffic is
allowed. Glover[21] describes these clearances as esti-
mates of the increase in the channel width occupied by
vessels that are necessary to compensate for such indeter-
minate factors as the ability of the pilot to maintain the
desired course, variable effects of wind and waves, and
any additional width required to ensure safe navigation.
Bank suction, the phenomenon of asymmetric pressure dis-
tributions on the hulls of vessels sailing off the axis of
channels, which results in nonzero equilibrium drift
angles, is an important factor contributing to the need
for lateral clearances. The Corps of Engineers in the
Draft Engineering Manual EM110-2-1611, 1980,[22] "Layout
and Design of Shallow Waterways," presents the recommen-
dations in Table V-1 as a guide for the minimum channel
widths required for tows of various sizes:

Table V-1

Recommended Channel Widths
after E.M. 1110-2-1611, 1980

Tow Width, Feet	Channel Width, Feet	
	Two-Way Traffic	One-Way Traffic
105	300	185
70	230	150
50	120	130

According to the engineering Manual, the minimum
channel widths presented are based on operating experience
which has indicated that the minimum clearance required
for reasonably safe navigation in the straight reaches
should be at least 20 feet between tow and channel limits
for two-way traffic, 40 feet for one-way traffic, and at
least 50 feet between tows when passing. Channel widths
of less than 130 feet are not recommended by the Corps for
commercial traffic.

A table of suggested channel dimensions published by Daggett and Shows[23] of WES, excerpted in Table V-2, recommends a minimum total of 50 feet for all clearances for 400 foot tows, and increasing total clearances for longer tows, up to 300 feet for 1300 foot tows. Daggett and Show cite Davis[24] as the source of the channel widths. Davis states that the channel widths shown are the minimum compatible with the lock sizes recommended for the tows, without explaining the basis for his selection.

Hochstein suggests a total channel width, W:

$$W = 2(L \sin \alpha + B) + 35 \text{ feet}$$

where L is the length, B is the width, and α is the drift angle of the tow. The value of α depends on the tow size and configuration, towboat power and propulsion and steering systems, channel dimensions, and wind and current conditions. Typical values are on the order of one to four degrees, about half of which is an equilibrium drift angle resulting from bank suction. The other half is transient, the result of perturbations due to wind, currents, and passing tows. Hochstein suggests an average value of .06 for $\sin \alpha$ in the absence of more detailed information on the effects of the parameters described above.

Hochstein[25] in an earlier paper presents a different method which attempts to account for the effects of wind and tow speed explicitly. The channel width for two-way traffic is given by:

$$W = 2 (L \sin \alpha + B \cos \alpha)$$

where W is the channel width, and 2 is the drift angle. No additional clearance is needed as 2 is estimated generously by the following formula:

$$\alpha = \sin^{-1} \left\{ \frac{V_w \, \gamma \, \sin \psi}{V} \right\}$$

where α is the drift angle, V_w is the wind speed, γ is the "sail factor" related to the projected surface area of the tow, ψ is the angle between the wind direction and tow heading, and V is the tow speed. The value of γ may be taken as .075 for empty tows and .025 for loaded tows. A

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Table V-2

Recommended channel Widths
After Daggett and Shows

Recom-mended Channel Width, Ft	Number Barges	Barge Size, Ft Width	Barge Size, Ft Length	Towboat Length, Ft	Width	Length
		Tow Makeup			Tow Size	
150	1	50	300	100	50	400
	2	35	195	100	35	490
200	2	35	195	100	70	295
	3	26	175	100	78	275
225	2	35	195	100	70	295
	3	35	195	*	70	390
	5	26	175	*	78	350
250	6	35	195	115	70	700
	10	26	175	*	78	700
	2	50	300	100	50	700
250	8	35	195	*	105	585
	10	26	175	*	104	525
	4	50	240	115	100	595
	8	35	200	*	105	600
300	11	35	195	*	105	780
	11	35	200	*	105	800
	14	26	175	*	104	700
	4	50	300	125	100	725
400	15	35	195	150	105	1,125
	15	35	200	150	105	1,150
	22	26	175	150	104	1,050
	8	50	250	150	100	1,150
500	18	35	195	160	105	1,330
	18	35	200	160	105	1,360
	8	50	300	160	100	1,360
	10	50	240	160	100	1,360
	8	50	250	160	100	1,160

*towboat does not control tow length.

20 mph cross wind acting on a light tow moving at 10 mph would yield a value of α of 8.6 degrees.

Balanin[26] presents a formula similar to the earlier Hochstein formula:

$$W = 2(L \sin \alpha + \frac{B}{2} \cos \alpha) + C$$

where W is the channel width for two-way traffic, α is the drift angle, and C is the sum of all clearances. No values of α are presented.

European standards on channel width clearances vary. They are generally oriented towards conditions in canals. Model tests performed by Kooman[27] led to his recommendation of a 30m (98.4') lane for a 2x2 push tow 191mx22.8m (626.5'x78.8'). He further recommends that a width 35m (114.8') be available for oncoming traffic. A channel width of 70m (229.6') with two-way traffic each 22.8m (74.8') across would result in a total clearance of 24.4m (80').

The Main-Danube Canal described by Wiedermann[28] was designed for two-way traffic with beams of 9.5m (31.2'). The channel in trapezoidal sections is 31m (101.7') wide at the bottom, yielding 12m (39.4') of total clearance. The Rhine-Scheldt Canal, discussed in the same paper, was designed to accommodate three lanes of traffic up to 24m (78.7') across. Model testing led to the design channel width of 120m (393.6'). Three lanes of maximum sized vessels would leave (157.4') of clearance.

If the clearance between tows is assumed to be twice the clearance between the outer tows and the banks, then the clearance between tows would be 16m (52.5') and the clearance off the banks 9m (26.2').

Schäle (22), on the basis of his research, recommends channel widths of 100m (328') for two-way passage of 2x2 tows 85mx22.8m (606.8'x74.8') and 60m (196.8') for 1x2 tows 185mx11.4m (606.8'x37.4').

A direct comparison of design formulas with the Corps Engineering Manual recommendations is difficult because the E.M. recommended minimum required width is insensitive to tow length. However assuming the most

common tow configurations a comparison of the various design standards for minimum required channel widths reveals the following:

(a) For typical 50 foot wide tows (about 400 feet in length) Daggett and Shows minimum recommended width is about 20% more narrow than that recommended by the Corps Engineering Manual or Hochstein's formula, (which provide identical values).

(b) For typical 70 foot wide tows (about 700 feet in length) Daggett and Shows and Hochstein's minimum recommended widths differ by about 25%, with Hochstein's formula giving the most conservative value. The minimum channel width recommended by the Corps of Engineering Manual falls midway between the two.

(c) For 105 foot wide tows the Corps Engineering Manual's minimum recommended width of 300 feet does not show the effect of different possible tow lengths. The E.M. minimum recommended width agrees with the other recommendations for tows having lengths less than about 800 feet. For tows of greater lengths, Daggett and Shows recommended widths are considerably larger than the E.M.'s 300 feet and Hochstein's formula gives values which are greater than the E.M.'s 300 feet but considerably smaller than those recommended by Daggett and Shows.

Hochstein's method has the advantages of being immediately applicable to all tow sizes and having a more sound theoretical basis. Hochstein's earlier method, while theoretically interesting because it attempts to account for the effects of wind, tow speed, and projected area explicitly, falls short as a design tool. The drift angles and widths suggested by the formulas are much larger than those appearing in practice. Most of the European standards are narrower than the American Design rules would suggest, except for those of Schäle, which are extremely generous. Nearly all of these standards are

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based on model tests, but the assumptions of the experimenters as to the propulsion and steering systems of the tows and environmental conditions, critical factors in the design channel widths, are not available.

A comparison between minimum recommended channel widths from the design standards are compared with actual widths existing on individual United States waterways in the NWS report, "Analysis of Waterways System Capability," (Table V-1). In general, the comparison reveals that many existing channels have widths which are considerably narrower than recommended minimum channel widths. In regard to this, the nature of the recommended standards must be considered. The standards represent unrestricted widths for safe navigation. For an actual waterway, vessel size which a channel can accommodate depends upon the frequency of restricted reaches, currents, towboat horsepower, pilot experience and many other factors, in addition to channel width. (Note: E.M. design standards do take into account the effect of currents.) Therefore, actual channel dimensions which may be narrower than recommended does not mean that larger vessels cannot be accommodated. Rather, it reflects a higher level of restriction, longer transit times and higher risk of operation than would be expected if the recommended width were available throughout the waterway.

2. Approach Channels to Coastal Ports. Channel width standards for coastal port entrances have been largely based on the experience of pilots and on research with physical models PIANC recommends[29] channel widths of three to four times the beam of the design vessel, if there is to be no passing; if vessels pass, the channel width should be six to seven times the beam of the design vessel. These criteria are based on ideal conditions, and additional allowance should be made for crosswind and crosscurrents.

An advancement to the design of coastal port channels applies the methods above as input into ship simulators such as the National Maritime Research Center's Computer Aided Operation Research Facility, (CAORF). These ship simulators list human piloting response coupled with ship maneuverability characteristics under various environments against a channel design. This tool is gaining rapid popularity.

One method of determining required coastal channel width is based on research conducted in connection with a sea level Panama Canal. This method divides the total channel width into (a) width of the maneuvering lane, (b) width of the ship clearance lane and (c) width of bank clearance.

The maneuvering lane is analogous to a car lane on a highway. Experimentally, a vessel navigating within this lane will not be hindered by the channel banks or another vessel. The width of the maneuvering lane for a vessel depends upon the controllability of the vessel. The controllability of various vessels was defined as follows:

(a) Very Good for naval fighting vessels and freighters of the Victory ship class.

(b) Good for naval transports and tenders, T-2 tankers, new ore ships and freighters of the Liberty ship class.

(c) Poor for old ore ships and damaged vessels.

Based upon this classification, the criteria shown in Table V-3 were recommended for a ship navigating the quarter point of the channel. A maneuvering lane equal to 140% of the vessel's beam was recommended for a ship on the centerline of the channel, regardless of controllability.

Table V-3

Maneuvering Lane Width at Quarter Mile

Controllability	Width in %
Very good	160
Good	180
Poor	220

*percent of vessel beam.

The criteria presented for the width of the maneuvering lane are for ideal conditions. They should be considered as minimum requirements.

Allowance must be made for the yaw of a ship if crosscurrents or crosswinds occur in the channel. A vessel 700 feet (213 meters) long with a beam of 90 feet (27 meters) yawing five degrees would require a channel width of approximately 180 feet (55 meters) just for yawing. A yawing of five degrees is reasonable for a vesse of this size in a semiprotected waterway subject to crosswinds and crosscurrents. It is suggested that the maneuvering lane width be the sum of the yawing width plus 60, 80 or 100% of the vessel's beam for very good, good and poor controllability, respectively.

The width of the ship clearance lane is measured between maneuvering lanes. The hydraulic phenomena associated with ships passing in a channel creates suction and repulsion forces between the ships. The width of the ship clearance lane is established to minimize the hazards of these forces. The minimum width desired by many pilots and navigators is 100 feet (30.5 meters).

When a vessel departs from the centerline of the channel and approaches the banks, the suction and repulsion forces create yawing moments. A rudder angle has to be applied to compensate for these forces in order to maintain a straight course. The rudder angle necessary for a vessel to maintain a straight course at a given speed, water depth and distance from the bank is called equilibrium rudder angle.

Studies by the Panama Canal engineers led them to conclude that the bank clearance should be based upon an equilibrium angle of five degrees. This criterion would permit an additional rudder deflection of 30 degrees on most ships. Based upon a five degree equilibrium angle and upon the results of the sea level Panama Canal studies, according to Wicker, McAleer and Johnston,[30] it is unwise to accept a bank clearance lane width of less than 60% of the beam of the vessel and unduly conservative to provide more without additional evidence to support lower or higher values.

Factors which would necessitate increasing the bank clearance over 60% of the beam of the design vessel are (a) poor maneuverability of the vessel, (b) speed of the vessel, if greater than five knots, (c) crosscurrents and crosswinds, (d) erodible banks and (e) wide waterways not confined by visible banks which define the approximate toe of the channel side slopes. Typical design of channel

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widths based upon criteria resulting from the sea level Panama Canal studies are shown in Figure V-B.

Using a bank clearance of 150% of the beam of the vessel would appear to give results slightly greater than the widths which would be obtained by applying the PIANC criteria.

(b) Bendways

In making a turn, the stern of a tow is moved laterally in a direction opposite to the direction of the turn. If the hydrodynamic forces and moments due to the rudders, propulsion system, hull pressure distribution, and the slope of water surface are allowed to equilibrate, the tow will assume and maintain an angle to the channel alignment which is called the deflection or drift angle. The required width of the channel is a function of the deflection angle and the length and width of the tow.

There are several formulations for required channel width as a function of the drift angle available in the literature; this section presents some of them, with numerical comparisons for common tow sizes. The experimental determinations of drift angle, and its sensitivity to various parameters, are also discussed.

1. Bouwmeester's Formulation. Bouwmeester[31] and De Ruiter[32] state that the extra channel width required in bends is a function only of the length of the tow, provided that the radius of the bend is at least three times the length of the tow, and the drift angle is greater than three or four degrees. Thus, design channel width for two-way traffic is given by

$$W = 2(L \sin \alpha + B) + C$$

where W is the width of the channel, L is the length of the tow, α is the drift angle shown in Figure V-C, B is the width of the tow, and C is the desired total clearance. R is the radius of curvature along the concave bank.

2. Corps of Engineers Formulation. According to the Draft Engineering Manuel, EM110-2-1611, "Layout and Design of Shallow Draft Waterways," if the deflection angle assumed by a tow is known, a reasonably accurate

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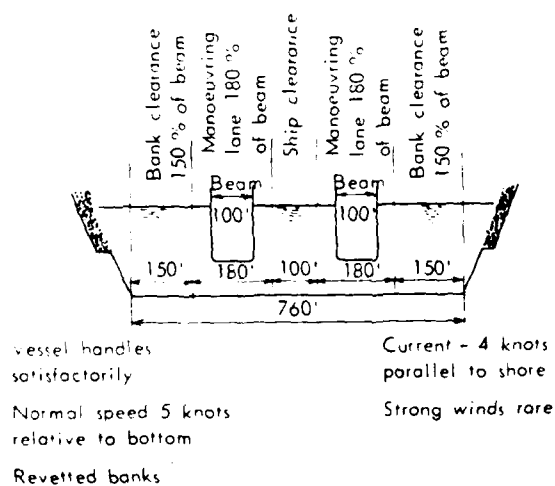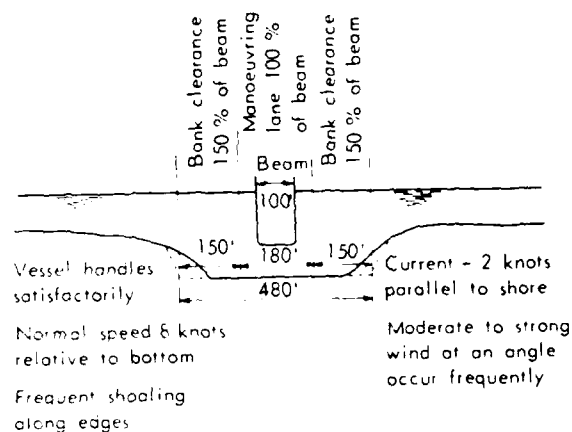
Figure V-B

Typical width calculatons ship channel after Hay, "Harbour Entrances, Channels, and Turning Basins," The Dock and Harbour Authority 4 (Jan): 269-76.

Figure V-C

Definition of Drift Angle in Bendways
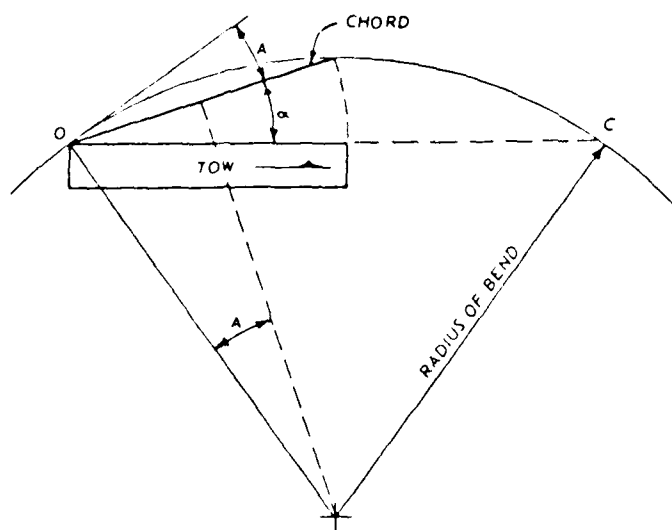
LEGEND

CHORD = LENGTH OF TOW

A = CHORD ANGLE

α = DEFLECTION ANGLE

O - C CHORD BASED ON TOW ALIGNMENT
MOVING THROUGH THE BENDWAY

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channel width required can be determined from the follow-
ing equations:

For one-way traffic:

$$W = (\sin \alpha d \times L_1) + W_1 + 2C$$

For two-way traffic:

$$W = (\sin \alpha u \times L_1) + W_1 + (\sin \alpha d \times L_2) + W_2 + 2C = C_t$$

where:

αd = maximum deflection angle of a downbound tow, degrees.

αu = maximum deflection angle of an upbound tow, degrees.

$L_{1,2}$ = length of vessels 1 and 2, feet.

$W_{1,2}$ = width of vessels 1 and 2, feet.

C = clearance required between tow and channel limit for safe navigation, feet

C_t = minimum clearance required between passing tows for safe two-way navigation, feet.

3. Ballin's Formulation. Ballin[33] suggests this approximate formulation for channel width:

$$W = \sin \alpha + B + R - (R + \frac{2L}{3}) \times (R - \frac{2L}{3}) + 2C$$

where w, L, α, B, C, and R are defined above. This equation is not dimensionally consistant and the result of squaring the bend radius is that large negative values for the channel width are obtained.

4. INSA Formulations. Appendix E of INSA[34] cites the method of Hartung[35]

$$W = \alpha \left[\frac{4R^2 - (L^2 + B^2)}{4R^2 - \alpha^2} \right]^{1/2} + 2C$$

where a = L sin α + B cos α. An empirical formula for the
drift angle   is given as well

$$\alpha = \tan^{-1} \frac{L}{2R - (L^2/2R + B)}$$

These various formulations for channel width in
bendways have superficial differences, but their substance
is all the same. Each is a geometric analysis of the
space occupied by tows on bends; the differences arise
largely from the definitions of the drift angle and the
use of approximations. The validity of any of these
formulations is governed by the value of the drift angle.
The determinations of   by various authors are described
in the following section.

5.   Determination of Drift Angle.   Glover[36]
performed model tests at various scales in order to
determine appropriate drift angles for channel design. He
tested models at scales of 1:80, 1:100, and 1:120 and
detected no scale effect over this range. His results and
a large number of model tests form the basis of the recom-
mendations in the draft Engineer Manual. Drift angles
recommended by the Engineer Manual consider six config-
urations of tows common on American waterways and bends
ranging from 500 feet up to 10,000 feet in radius. All
tows were loaded to a scale draft of eight feet in a nine
foot channel. The tow speed was maintained at steerage
way - just enough speed so that the tow could maneuver.
The findings for drift angles are shown in Figures V-D and
V-E for 110'x600' and 110'x1200' tows. Similar figure are
also available for 35'x480', 35'x685', 20'x480' and
70'x685' tows. The Engineer Manual recommendations should
not be applied indiscriminately to channel design. The
model channel is idealized with a normal current distribu-
tion. River currents in natural streams are affected by
various factors, including the alignment of the channel
upstream and the existence of hard points and irregular
bank lines. These anomalies can affect the drift angle of
tows. In addition, the model tests are based on tows just
maintaining steerageway around the bend with the minimum
possible depth. Higher powered tows, those with specially
designed rudders or auxiliary steering devices, those
choosing to maneuver with differential engine power and
those operated in deeper channels, will require less space
in bendways than the models. Underpowered tows which
would flank through the bends will require more channel
width in order to drive straight through. In comparison
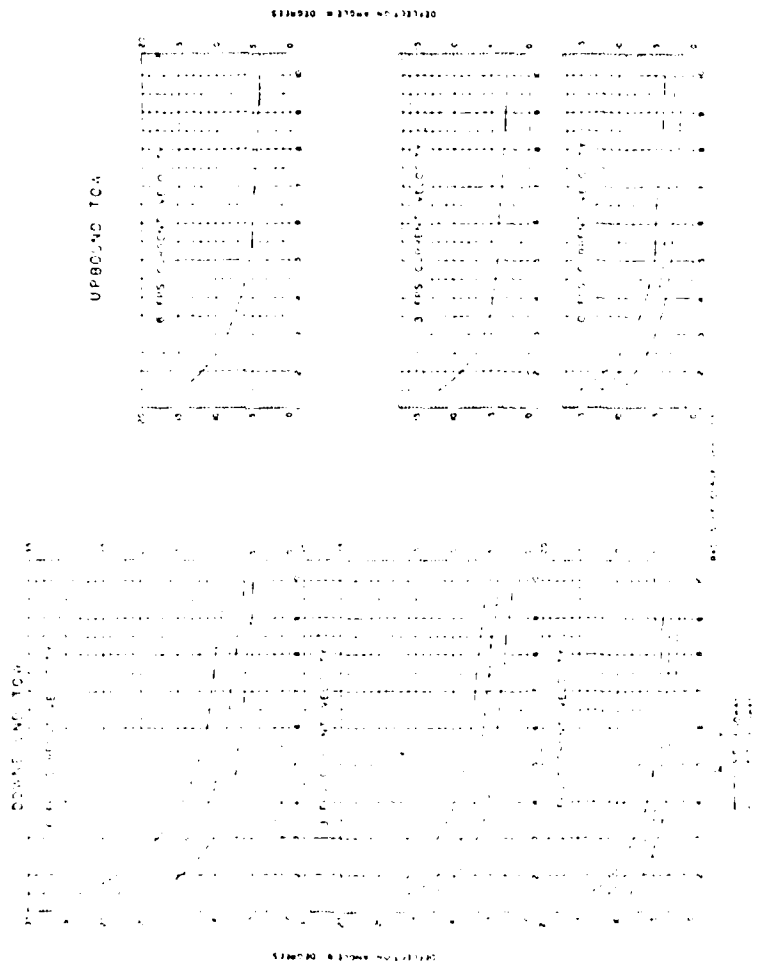
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Figure V-D

Deflection angle for tows driving through bends forming uniform curves. Tow size:
105 feet wide by 600 feet long, submerged 8 feet.
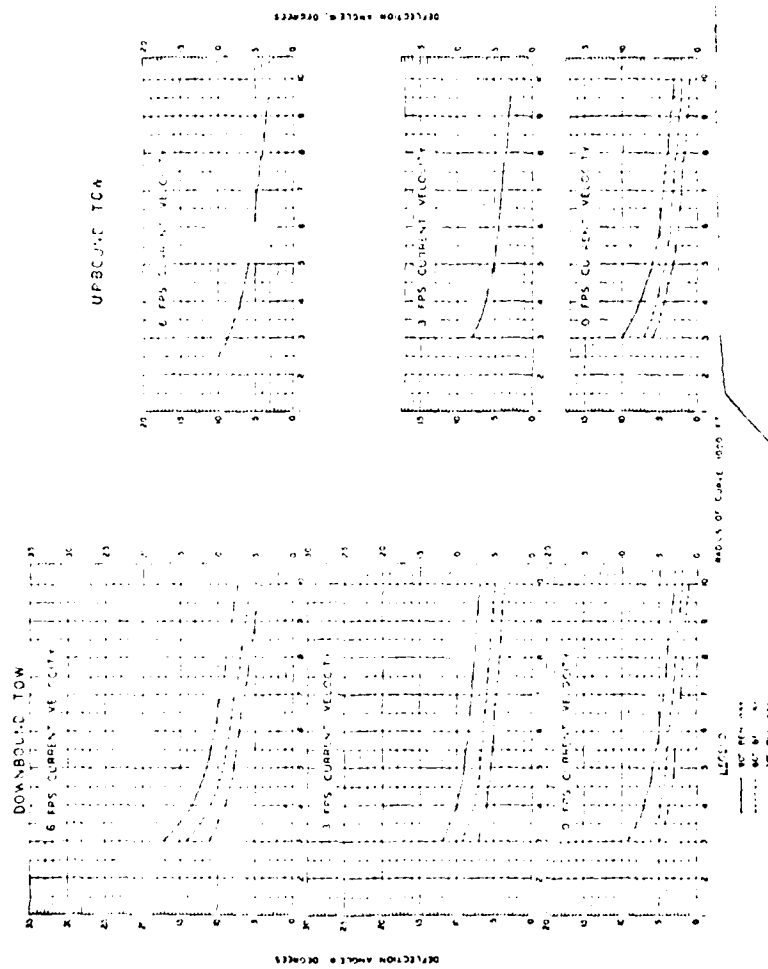
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Figure V-E

Deflection angle for tows driving through bends forming uniform curves. Tow size: 105 feet wide by 1200 feet long, submerged 8 feet.

with actual experience, the E.M.'s drift angles represent the lower limit of maneuverability of tows, and thus lead to generous channel widths. Such widths are rarely available on sharp bends in the United States.

De Ruiter describes 1:25 scale model tests which are also discussed by Bouwmeester. He considers the effects of various parameters on the drift angle of tows, but the direct applicability of his results to waterways in the United States is questionable. The Dutch Rijkswaterstaat (Ministry of Public Works) which sponsored De Ruiter's work is naturally concerned with European waterways, which are often canals with cross sections that are far more restricted than those of American waterways. Minimum required depth-to-depth ratios in Europe are higher than in the United States, and the model tests reflect this. De Ruiter considers depth ratios in the range of 1.3 to 6, compared to the ratio in the E.M. of 1.1. De Ruiter states, for example, that at a depth ratio of 1.3, the drift angle is always less than five degrees and increases with the depth ratio. This result is contradicted for the draft Engineering Manual which contains values for the drift angle recalculated in accordance with De Ruiter's definition. The conclusion also appears specious in light of a wide body of hydrodynamic theory and observation, which states that the maneuverability of vessels increases with depth ratio.

The INSA program's report, "Waterway Analysis" cites an empirical formula presented by Hartung for drift angle. The values which can be calculated by this formula are lower than those found in the Engineer Manual, which suggests that they may be more appropriate for typical, as opposed to extreme, cases. (Note: in the INSA report, the effect of current velocity on drift angle is ignored, model tests at WES have shown this effect to be significant.)

Table V-4 presents a comparison of the channel width required in bendways according to various formulations and determinations of drift angle. It is important to note that this comparison is based on one fixed bend radius. Radius and channel width are directly related, and an infinite number of different width-radius combinations may be equally acceptable from the point of view of unrestricted navigation. The designer must consider the economic trade-offs involved in the selection of a specific width-radius pair.

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Table V-4

Drift Angles and Channel Widths in Bends

Tow	(1) Drift Angle E.M.	(2) Channel Width E.M.	(3) Channel Width INSA***	(4) Drift Angle INSA***	(5) Channel Width INSA***	(6) Drift Angle De Ruiter
I 105'x1200'	10.0	716	693	8.5	631	–
II 105'x600'	9.5	498	479	4.2	371	10.8
III 70'x685'	8.8	440	421	4.8	329	9.2
IV 75'x685'	8.0	350	335	4.8*	259	7.9**

*downbound tows
3 fps current
R = 4100'
90 degree bend

** II   34.2mx191m (113'x626') downbound tows
III 22.8mx191m (75'x626') 1m/sec (3 fps) current
IV   11.4mx191m (37'x626') R = 1240m (4067')
90 degree bend

***Empirical formula presented by Hartung and cited by INSA.

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Four common tow sizes are used in the comparison. The drift angles are selected for the following conditions:

- downbound tows.

- 3 fps current.

- 4100 foot bend radius.

- 90 degree bend.

Column 1 contains the drift angles appropriate for the condition described above chosen from the Engineer Manual. Column 2 presents the width required, calculated according to the method of the Engineer Manual, using 90 foot total clearance as described in the Engineer Manual. Column 3 presents the width according to the INSA formulation, using the drift angle of the Engineer Manual and the 75 foot total clearance suggested by INSA. Column 4 and 5 contain the INSA calculted drift angle and width. Column 6 contains the drift angles according to De Ruiter for European tows similar in size to American vessels and slightly different conditions. De Ruiter does not present any recommendation for total channel width in bendways.

Column 4 and 5 differ from Columns 1 - 3 reflecting the difference between the drift angles determined by the E.M. in model tests and by INSA with an empirical formula. The E.M. experiments model extreme conditions - the tows have barely enough power to drive through the bends and the water is shallow. The INSA formula for drift angle is based on more typical conditions and yields more moderate drift angles. Therefore, the INSA empirical formulation is more appropriate for a general examination of the degree of restriction at bends. Dr. Larry Daggett of WES is currently beginning a theoretical study of the behavior of shallow draft tows in bends with the goal of developing a mathematical model which can be used for channel design.

Comparing values obtaining using the INSA formula and the recommendations of the Engineer Manual, the values obtained using the INSA formula are closer to typical conditions. As previously stated, channel design standards of the Engineer Manual do not present absolute limits but, rather, reflect conditions required for unrestricted navigation.

Column 6 is based on the limited amount of data shown in De Ruiter. The depth ratio in the experiment during which these drift angles were measured was 2:1. That they correspond to Glover's experiments at a depth ratio of 1.1:1 is either a coincidence or an indication that depth ratio has little effect on drift angle. The weight of the analytic and experimental evidence suggests that the former explanation is correct. De Ruiter's complete data is available only in Dutch, and could not be examined in this report.

CHANNEL RADIUS OF CURVATURE AT BENDS

(a) Inland Waterways

The required minimum radius of curvature of bends is clearly related to the channel width. Figure V-D illustrates how drift angle, and thus increased channel width, increase inversely with bend radius. Any of the formulations for channel width shown above can be solved iteratively for the required bend radius given a channel width. Bend radius is included implicitly, at least, in all of the formulations through the dependence of drift angle on the radius. "Waterway Analysis" includes an approximation for the required increase in channel width that is particularly amenable to this procedure:

$$W = \frac{L^2}{2R}$$

where W is the channel width not including clearances. Rearranging,

$$R = \frac{L^2}{2W}$$

Some additional guidance may be obtained from the results of European research shown in Figure V-F. Figure V-G presents the radius requirement guideline followed by West Germany.[37] The "maneuvering width" in the figures is the sum of the beam of the vessel and the increased width required because of the bend. As a rule-of-thumb, the Conference of European Ministers of Transport recommends that bend radius be not be less than 10 times the length of the design vessel.

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Figure V-F

Maneuvering Widths v.s. Bend Radius (after Schale)
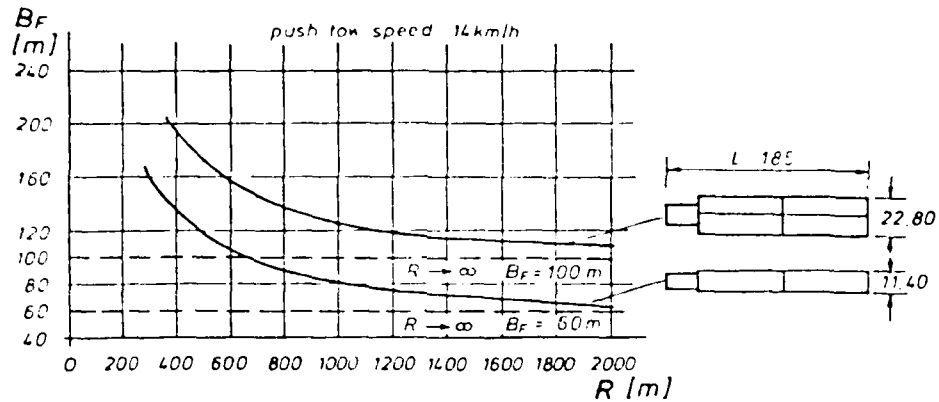
Figure V-G

Maneuvering Width v.s. Bend Radius for the
Rhine-Main-Danube Waterway (after Kuhn (23))

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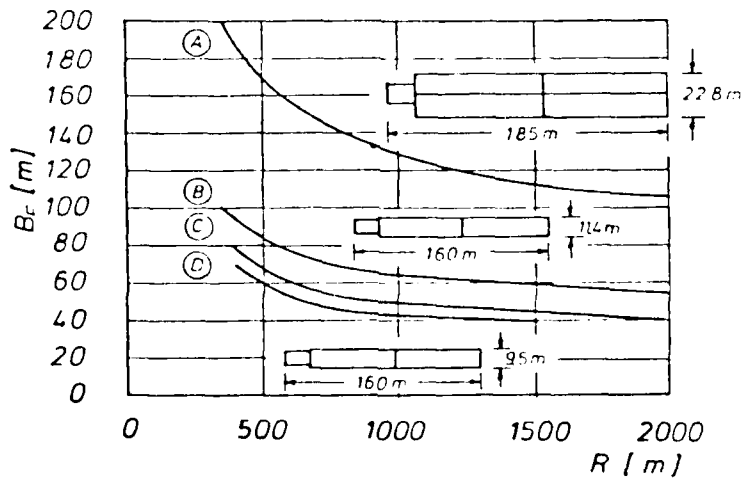
A further consideration in the selection of bend radius, discussed by Glover, is the sediment load of the river. It may be more economical, initially, to construct a shorter radius with a wider channel, but a river that carries a substantial bed load might not be able to maintain design depth in the widened channel without training works.

(b) Approach
    Channels to
    Coastal Ports

The problem of bend radius in coastal port approaches is somewhat similar to that of inland waterway channels. A channel should be aligned to provide navigation without subjections to difficult maneuvers and strong crosscurrents. Consideration should also be given to the alignment of the channel with respect to shoaling and littoral drift.

The ideal channel should be free from curves. This is rarely obtained in rivers and harbor areas where the topography or layout often requires a direction change in the channel. The general conclusions of the 20th Session of PIANC with respect to channel alignment were that the channel should be reasonably straight, free from S curves and perpendicular to the shoreline, unless there is a predominant storm direction; in that case, head into the storm direction. The suggestion that the general conclusions of the Congress include that the channel should not follow a component of a current was negated.

When a direction change is necessary in a channel, many navigators prefer a series of short tangents connected by short curves. It has been suggested that for a maximum 30 degree deflection angle, the length of the tangents should not be less than 3,000 feet (914 meters.[38] The radius of curvature, R, and the deflection angle, a, are shown on the unwidened curve in Figure V-H. It is evident in this figure that for a given radius the length of the curve will increase with an increased deflection angle.

Figure V-H
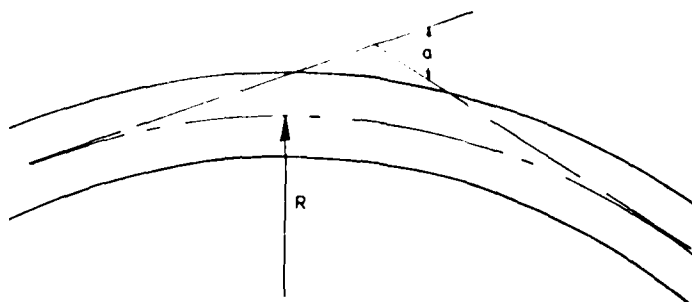
Radius of curvature and deflection angle in channel bend
after Hay "Harbor Entrances, Channels, and Turning Basins,"
The Dock and Harbor Authority 4 (Jan) 269.

The ease with which a long curve may be navigated depends upon the controllability of the vessel. When a vessel turns under its own power, the centerline of the vessel is almost tangent to the curve which the bow follows. Usually a constant rudder angle cannot be maintained to navigate a constant radius. The varying degrees of controllability of ships coupled with the individual techniques of navigators has led to the presentation of varying criteria for minimum radius of curvature and maximum deflection angles desirable to channels. Some existing canals have widely varying maximum deflection angles: for example: Gaillard cut, Panama Canal, 30 degrees; Suez Canal, 63 degrees; Cape Cod Canal, 75 degrees; Houston Ship Channel, 109 degrees. The maximum deflection angle for the proposed sea level Panama Canal is 26 degrees with a radius of curvature of 12,500 feet (3,810 meters).

The minimum sight distance required by navigators while traversing channel bends has never been clealy established. The proposed sea level Panama Canal is designed for a minimum slight distance of 1.52 miles (2.44 kilometers.[39] In many areas a sight distance of half a mile (0.8 kilometers) would be adequate.

It is common practice to widen a channel in a bend to allow for the swing of the vessel and to provide increasing maneuvering width. The three methods commonly employed for widening a channel at a bend are (a) the cutoff method, (b) the parallel banks method and (c) the non-parallel banks method. These three methods are shown in Figure V-I. The St. Lawrence seaway uses the cutoff method by increasing the width at the point of intersection of the inside tangents by 10 feet, (3.05 meters) for every degree of deflection. The cutoff method requires less dredging than the other two methods mentioned, but it was observed during the model studies for the sea level Panama Canal that the cutoff method produced undesirable current pattterns.

CHANNEL RADIUS OF
 CURVATURE

The cross sectional area of a channel usually need be considered only in canals, because natural rivers, espe-

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Figure V-I

Methods of Widening Channel at Bends
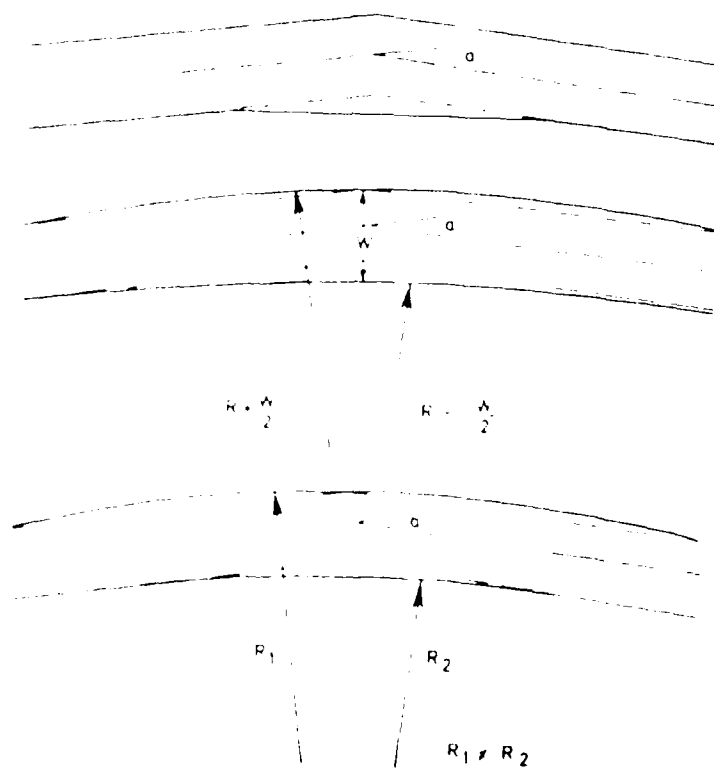
cially in the United States, channel cross sections will be discussed only briefly.

Speed and resistance are the main considerations in the selection of a cross sectional area standard. The ratio of the cross sectional area of the channel to the maximum cross sectional area of the design vessel is called the blockage ratio. When this ratio is less than seven or eight, the drag on vessels is increased, and a limiting speed is imposed. The limiting speed is given by:

$$V_l = 1.97 \sqrt{\cos^3 \left| \frac{\pi + \cos^{-1}(1 - 1/A)}{3} \right|} \sqrt{gh}$$

where V_l is the limiting speed, A is the blockage ratio, g is the acceleration due to gravity, and h is depth.

Dynamic sinkage, or squat, is a function of the channel cross section as well as depth and speed. Figure V-J illustrates this effect. The lowering of the water level, or squat, is shown as a function of tow speed. Solid lines are plotted for a 100m (328') wide channel at various depths, and dashed lines for a 31m (101.7') channel. Deeper squat appears at slower speeds in narrower channels. The design condition for cross section due to squat is often the passage of two vessels, or in some cases, overtaking with an oncoming vessel reduces the available cross section for the others and increases their squat.

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Figure V-J

Squat v.s. Tow Speed for Various Depths and Channel Widths
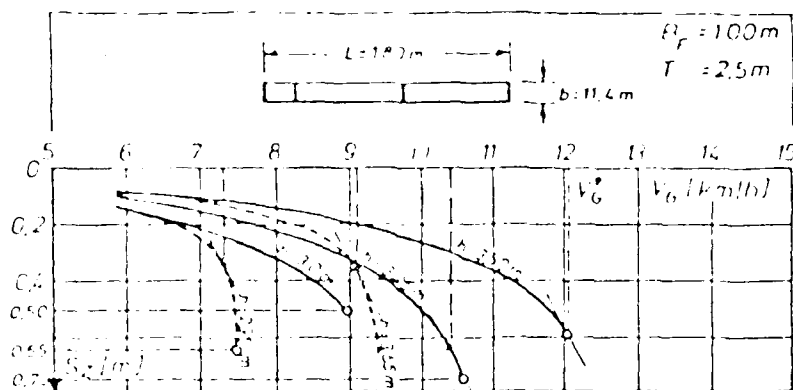
B_Γ = manevering width

T   = Draft

S_z = Sqat, m

solid lines represent squat vs. tow speed in a 100m wide channel.
Dashed lines represent squat vs. tow speed in a 31m channel.

VI - RIVER TRAINING TECHNOLOGY

River training involves the use of channel improvement and stabilization structures to control a rivers' behavior. The natural tendency of a river to shift across its valley often prohibits productive use of these lands. Sinuous channels tend to slow the passage of flood waters and increase the risk of flooding to riparian cities, harbors, and industries. After passage of flood flows a river will typically display a channel that in many places will be too shallow, too narrow, or too tortous for navigation. The purpose, then, of river training is to encourage the river to develop a channel with the dimension and alignment which will carry flood flows and be suitable for navigation.

Rivers are extremely complex and changes within these rivers depend upon many interrelated hydrologic and morphologic factors. The principal factors include channel geometry, discharge, water level gradient, and the composition of the channel bed, sediments and banks. For navigation interests the main purpose of river training is to improve channel depths and alignment and to stabilize the channel through the construction of regulating structures. The type of training structures is dependent upon the characteristics of the particular river, the availability of construction materials, and, to some extent, on the equipment expected to use the waterway.

Many rivers or reaches of rivers have been found unsuitable for river training to improve navigation and the only options were the construction of locks and dams and/or dredging. Generally, locks and dams have been required in rivers characterized by having steep slopes with resulting high water velocities, seasonally inadequate depths, or where conditions such as rock outcrops, high sediment loads, or critical flood carrying capacities prevent the use of training structures.

The single most significant problem in providing a navigable channel relates to the movement and deposition of sediment within the channel. Sedimentation effects the depth, width, and alignment of the channel; the operation and use of facilities and structures for navigation such

as locks, harbors, and docking areas; and other facilities
such as hydropower units, sewage disposal, and water
intakes.

Considerable research has been undertaken in order to
understand the nature of sediment movement. Many impor-
tant advancements have been achieved in the development of
basic theories for use in computing sediment loads. The
formulas for computing bedload transport are, nonetheless,
subject to large errors with accuracies obtainable only to
an order of magnitude unless modified utilizing a wide
range of sediment data collected from the particular river
reach in question. For the most part, however, little
practical information can be found on the control of sedi-
ment in natural reaches. There is presently insufficient
knowledge in certain areas of river training to be devel-
oped. As a result most river training is conducted on a
subjective basis by experienced engineers with only gen-
eral guidelines and physical and/or mathematical models to
aid their decisions.

A brief review of the more significant elements in
river mechanics is included in the following sections.

RIVER CHARACTERISTICS
 AND CHANNEL STABILITY

    (a)   Sediment
        Properties

The individual properties of sediment are a signifi-
cant factor in the study of alluvial channels. In hy-
draulic engineering the size of sediments, the fall
velocity of a single particle or of a group of particles
and the specific weight of a single particle and charac-
teristics of deposited sediment are of importance. All of
the properties enter into computations on the effect of
river training structures on scour and deposition and the
dimensions of physical models.

The fall velocity and specific weight of sediment
particles are important variables used to estimate
resistance to flow and the rate of sediment transport.

The settling of particles has been the subject of
rather intensive studies during the past two decades.
However, because of the complexity of the subject emphasis
was placed on the settling properties of single parti-
cles. In turbid water and for very fine sediments it has
been noted that it may be more important to consider the
settling of flocs when evaluating responses in flat chan-
nel systems, such as reservoirs, estuaries, and embayments,
where turbulence and velocities are relatively small.

Often, the banks of alluvial channels are signifi-
cantly stratified consisting of layers and levels of both
cohesive and noncohesive alluviums. This adds to the
complexity of evaluating bank and channel stability. The
cohesion of natural soils is an important element in
hydraulic engineering and particularly in channel stabili-
zation calculations. While it is known that a factor of
cohesion exists in many soils it is a factor that is not
well understood and defined only by empirical relations.

(b) Bed Roughness

Bed roughness, or the geometric configuration assumed
by the bed surface in an alluvial channel plays a signifi-
cant role in determining the channel friction factor and
ultimately the sediment transport rate. The changes in
bed roughness or forms result from the interaction of the
flow, fluid, and bed material. Specifically, it is known
that the resistance to flow and sediment transport are
functions of the slope, discharge, and depth of the
stream, the fluid viscosity, and the size distribution of
the bed material. The analysis of flow in alluvial chan-
nels is most complex because of the interaction between
the flow and bed material and the interdependency among
the variables. At the present time, the physical theory
describing this interrelationship is incomplete.

Simons (40) has provided insights into the different
types of bed forms which occur in sand bed channels, the
resistance to flow and sediment transport associated with
each bed form and how the variables of depth, slope and
viscosity affect bed form. In reality it is probably
impossible to find a river with flow conditions which
produce only one form of bed roughness at a particular
point in time. Different bed, forms which occur in the

same channel cross section and their sum will be different from the resistance computed using several resistance formulas.

There are a number of methods in the literature which are utilized in calculating the resistance to flow in alluvial channels. These include Einstein and Barbarossa (1952), Simons and Richardson (1966), Richardson and Simons (1967), Alan and Kennedy (1969) and Senturk (1974). Each of these methods have their particular assets for specific channel conditions and it is recommended that, when available, field data be used to test the methods of calculation applied.

(c) Threshold
     Values of
     Motion

The observation of particles in laboratory experiments have shown that when the shear stress over the bed attains some critical value there is particle motion. When the drag force is less than some critical value the bed material of a channel remains at rest. In the field the initiation of movement is difficult to observe and, even in the laboratory, the exact moment of the initiation of movement is difficult to define.

Approaches to predict the initial movement of grains in bed material have evolved along two lines. The first approach has attempted to relate the threshold of movement to the velocity of fluid flow. Methods using this approach have been proposed by:

1. Fortier and Scobey (1926).

2. Several Russian Papers (1935, 1967, 1970, 1975).

3. United States Department of Agriculture, Soil Conservation Service (1977).

The second approach has attempted to relate to the threshold of movement to tractive forces. Methods using this approach have been proposed by:

- Shields (1936).

- United States Bureau of Reclamation (1959).

The Fortier and Scobey method was endorsed by the ASCE Committee on Irrigation Research and provide maximum permissible values of velocity. This method has had widespread use, even in recent years, in spite of its early development and the fact that most data upon which the concepts were established are from relatively low velocity canals that carried significantly quantities of fine sediment.

In order to take into account the effect of the relative density of suspended sediments on the maximum permissible velocity, I. Karasey; in "Riverbed Deformation," Hydrometeorology, Leningrad, 1975, recommended the following simple equations for computing critical velocity:

For clear water:

$$V_c = 3.6 \ (hd)^{0.25}$$

For flow with suspended sediments:

$$V_c = 3.6 \ \sqrt{1 + 3p^{2/3}} \ (hd)^{0.25}$$

where d = sediment partical diameter, in m.
h = flow depth, in m.
p = concentration of suspended sediments, in kg/m^3.

The Russian method has not been widely accepted in United States practice but after evaluation may be acceptable for an approximate evaluation of the critical velocity. For more precise calculations, a method to compute the maximum permissible velocity was recommended by Z.E. Mirzhchulava, "River Bed Erosion and Estimate of Its Stability," Moscow, 1967. The method provides analytical equations for both cohesive and non-cohesive soils

including as parameters, stability as a function of aver-
age or bottom flow velocity, the concentration of sus-
pended sediments, the depth of flow, the granulametric
structure and the molecular attraction of sediments and
other factors.

A procedure has been proposed by the United States
Department of Agriculture Soil Conservation Service,
(Technical Release No. 25, 1977) 41, which relates the
maximum permissible velocity to measurable stream
parameters. A basic relationship between grain size and
maximum permissible velocity has been developed along with
curves that show the basic relationship between the plas-
ticity index of cohesive material and the maximum permis-
sible velocity. These basic curves were derived using the
Fortier and Scobey information of 1926. The methods used
to determine the maximum permissible velocity have evolved
a great deal since Fortier and Scobey first attempted a
qualitative approach to stable channel design in 1926. In
this regard, the methods developed in the Union of Soviet
Socialist Republics deserve more attention

(d)   Sediment
Discharge

The amount of material that is transported and ulti-
mately deposited in a stream is a function of two sets of
variables. The first set relates to the quantity and
quality of sediment eroded into the stream. The second
set involves the capacity of the stream to transport the
sediment. The mechanics of sediment transport are so
complex that little optimism is expressed for the full
understanding of this process.

Studies of sediment transport have resulted in a broad
spectrum of equations. Such equations provide, in general
the expected capacity of a stream to transport sediment
under the given hydraulic conditions. The actual bed load
transportation may be considerably reduced under river
conditions because of unsteady flow regimes that results
in non uniform channels and the intermittent transport and
deposition of sediment. Once deposited, sediments are
more resistant to transport, particularly silts and clays.

Sediment transport equations have been developed for particular channel types and a necessary requirement for the use of tne equations is the selection of the equation most suited for the channel in question. Field results will often dictate refinements in the existing equations. The most univerally acceptable sediment transport formulas include Meyer-Peter-Muller (1948), Einstein (1942), Colby (1964), Bishop et. al. (1965), Blench (1966), and Inglis-Lacy (1968).

(e) River Stability Indicators

Given the complexity of flow in alluvial channels described in the previous sub-sections and the lack of complete understanding of some of the basic processes involved the prediction of response to channel development is a very complex task. Quantitative prediction of the effects of river training can be reasonably accurate if the required data are available with sufficient accuracy. It is more often the case, however, that qualitative estimates must be relied upon because of lack of necessary data.

A number of researchers have developed qualitative relations that are useful in analysis of river response. They include the following:

1. Depth of flow y is proportional to water discharge Q.

2. Channel width W is proportional to both discharge Q and sediment discharge Q_s.

3. Channel shape, expressed as width to depth W/y ratio is related to sediment discharge Q_s.

4. Channel slope S is inversely proportional to water discharge Q and directly proportional to both sediment discharge Q_s and grain size D_{50}.

5. Sinuosity sd is directly proportional to valley slope and inversely proportional to sediment discharge Q_s.

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6.   Transport of bed material Q_S is directly related to stream power T_oU and concentration of fine material D_F, and inversely related to the fall diameter of the bed material D_{50}.

However, river stability is rather a qualitative parameter and can best be characterized by comparison with other rivers of similar size and hydrological conditions.

Analytical methods used to define river stability attempt to quantify relationships between morphological features and compare the values derived to similar values derived for rivers of known stability or instability.

Simons et. al. (1975) established a proportionality between bed material transport and several related parameters.

$$Q_s \sim \frac{(\gamma DS)\ WU}{d_{50}/C_F} = \frac{\gamma QS}{D_{50}/C_F}$$

Where   W = Channel width
         U = Cross sectional average velocity
         γ = Specific weight of the water - sediment
              merture
         D = Depth of flow
         S = Slope of energy gradient
         C_F = Concentration of fine sediment load
         d_{50} = Median diameter of bed material and
         Q = Total water-sediment discharge.

If specific weight is assumed constant and the concentration of fine material C_F is incorporated in the fall diameter, this relation can be expressed simple as QS Q_s d_{50}. This relation is identical to Lane's relation except d_{50} is the fall diameter of the representative sediment.

The proportionalities given above provide a useful first approximation in prediction the effect river training may have on a particular reach. The condition is relative and provides a comparison between rivers with different characteristics. Engineers responsible for river training projects often describe their work as being

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an art form, more often based on experience rather than any rigid criteria. However, qualitatively if not explicitly, the proportionalities serve as a guide in river training.

Consider, for example, the effect that artificial cutoffs have on a given reach. Obviously, cutoffs will increase channel slope. This increase in slope will cause higher velocities, increased bed material transport and possibly increased head cuts in the stream immediately above the reach in question. These changes in channel hydraulics could result in unstable banks, a braided stream form, and produce a drop in base level which would affect any tributary streams entering the reach. In order to retain the original channel characteistics in terms of its ability to transport sediment loads and to avoid bank instability through the straightened section, consideration may be given to a wider and shallower channel if sufficient depths are available for navigation.

Another example of the effects that river training may have on a channel is illustrated by the common practice of constructing dikes on the convex bend of a meander loop and revetment on the concave bank.

During low stages the thalweg tends to hug the outside of the meander loops except for the cross over reaches.

During high stages the thalweg tends to follow a shorter path because of higher velocities and momentum. The high stage thalweg tends to skirt the convex bank and cut across the tip of the point bar. his will sometimes produce a chute channel across the point thus dividing the flow and possibly becoming a hinderance to navigation.

Dikes and revetments are often constructed to prevent the development of chute channels and divided flow reaches. The effect of these structures on the hydraulics of the section can be analyzed qualitatively or by using physical and mathematical models. For example, in a natural undeveloped meandor loop the roughness (Manning's n) will decrease with increasing discharge. However, during high flows the water will tend to impinge on the dikes at

angles approaching 90 degrees, thus creating significant turbulence. The energy losses created by the turbulence as flow is diverted over or around a dike to generate backwater effects. If a field of dikes is created then there would be an even higher increase of flow energy losses.

The increase in energy loss caused by construction of a field of dikes will result in decreased velocity and increased stage upstream of the dike field. This will produce backwater effects and increase depths for a distance upstream of the dike field. This channel modification may provide a more desirable channel for navigation. However, backwater effects are usually only significant at high flow when depth is already sufficient for navigation. The backwater effect is small at low and intermediate flows during which depths are shallow and navigation depth may be a problem. Also, the increase in depth is only temporary because sediment will deposit upstream of dike field due to backwater effects. Additionally, channel stability will be affected by degradation in the main channel paralleling the dike field and aggradation can be expected downstream of the dike field. Therefore, long-term changes associated with construction of dikes required a more detailed look and the effects of dikes on dredging requirements must be quantitatively estimated.

(f)   Bank Stability

A great deal of work on the subjects of bank stability, bank erosion and bank protection for waterways has been performed in recent years.

A large volume of technical data was collected on the subject in the Ohio River Division for use in litigation actions. As part of the Ohio River Bank Erosion Study (Ohio River Division, July 1977) comprehensive information was gathered from historical files, published data, mappings, aerial photogaphs, field reconnaissance, and sampling and testing of materials in order to determine the cause of bank erosion at 22 specific sites along the Ohio River. A secondary objective was to use the data gathered in predicting potential erosion, its causes, extent and timing at other sites along the Ohio River and its tributaries.

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The Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, PL93-251 authorized a five year research program into problems of bank erosion. The report which is scheduled for completion 31 December 1981 has as its main objectives:

    1.   evaluation of the extent of streambank erosion, nationwide.

    2.   literature survey and evaluation of bank protection methods.

    3.   hydraulic research on the effectiveness of bank protection methods.

    4.   research on soil stability and the identification of the causes of streambank erosion.

    5.   demonstration programs on the Ohio, Missouri and Yazoo Rivers and on other streams, nationwide.

A great deal of information from the Section 32 Program is currently available in the form of preliminary reports.

Among the many factors which significantly influence the stability of a particular configuration of river banks are the characteristics of the soils and rocks at a particular site. Rivers flowing through areas of rock outcrops are generally quite stable. However, rock failures may occur if joints, faults, or bedding planes within the underlying rock are situated at unfavorable angles to the slope. Rock type is of course important is that weathering characteristics of individual rocks varies significantly.

Of far greater significance to bank stability is the characteristics of soils which occur along the banks of alluvial channels. If the alluvium is homogenous, the removal of individual grains or local mass failures tends to produce uniform banks since water flowing along the banks will tend to remove any projections. If sandy materials dominate the bank then the bank will assume an angle of repose which will then be reworked by erosion, piping, and stream action. If the bank consists of cohesive clay

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particles a near vertical face may be created. For example, silty clays provide streambanks which may be more than 75 feet high along the Mississippi River and remain stable for years.

Slope failures resulting from streambank erosion is a complex phenomenon but may generally be described from one or more of the following causes, according to the American *Society of Civil Engineers Task Committee on Channel Stabilization Works 42 (6).*

1. Attack at the toe of the underwater slope, leading to bank erosion and failure. The greatest period of bank failure normally occurs in a falling river at the medium stage or lower.

2. Erosion of the soil along the bank and bed caused by current action.

3. Sloughing of saturated cohesive banks, i.e. banks incapable of free drainage, due to rapid drawdown.

4. Flow slides (liquefaction) in saturated sandy soil.

5. Erosion of the soil by seepage out of the riverbank (piping) either at soil lenses at higher elevations or along the surface of seepage above the river water level.

6. Erosion of the upper bank, river bed, or both, due to wave action by wind or passing ships (including prop wash).

7. Headcutting (degradation of the river bottom progressing upstream) with consequent undercutting of the banks.

Bank erosion occurs when the critical velocity or the critical shear stress is exceeded for a particular bank or bed material. The nature and size of the bank material determine the critical velocity values. The attached figures show this relationship. Erosion is most active in the sand size range as the cohesion in the clay range and

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the weight of gravels both require higher velocities to initiate erosion.

Generally, sediment transport Q_s is proportional to the average velocity V raised on the fourth power.

$$Q_s \sim V^4$$

Typical velocities of rivers at low stages are 1.5 fps or less. All flood stages the average velocity in the channel will be on the order of 5 fps or more. The ratio of sediment transport during low stages and high stages may be hundreds of times larger $(5)^4/(1.5)^4 = 123$. It follows that almost all significant bank erosion occurs during periods of high discharge.

A second period in which significant bank erosion occurs is during the drawdown period immediately after flood flows. During high flows the riverbank soils become saturated. During drawdown, particularly if the soils are dominated by cohesive clays, the soils will retain water and consequently weigh more. Drainage is often further impeded by the horizontal layering component characteristic of alluvial soils, or by blockage of seepage exit points by debris or ice. Raising the center of gravity of a soil mass by increasing the water content in the upper layers thus tends to increase the possibility of bank failure.

In low density sandy soil liquefaction may occur producing flow slides. Saturation of these soils produces excess pore pressure that reduce the effective stress and consequently the shear strength to zero. Flow slides frequently occur on the convex bank near the point at which the maximum velocities impinge upon the river bank during flood stages.

Soil piping occurs when individual soil particles are removed from the riverbank as a result of surface infiltration, flood saturation, and subsequent seepage out of the bank face. Piping commonly occurs along sand filled desication cracks in cohesive lenses which are characteristically layered in alluvial soils. This reduces support for overlying soils and failure of blocks of soils often results.

Erosion may also occur from wave action produced by wind or ships. The height and period of waves generated by wind are a function of wind speed, water depth, and fetch length. The fetch length is probably most significant as a relatively long distance is necessary before waves of sufficient magnitude are produced which would cause erosion. The waves produced from ship navigation are a function of the vessel's hull design displacement compared to the channels cross section, the ratio of vessel width to channel width, speed of the vessel, and alignment of the sailing line with respect to the river alignment. Locally, erosion from waves and propellor action generated by ships has been found significant in some cases but generally this is not serious on a large scale. The most troublesome spots are typically, narrow channels, approach channels where forward and reversing of engines for maneuvering purposes often produces erosion of the channel bed and banks, and sharp bends where bank is exposed to propelled jet. The final judgment of the effect that navigation has on bank erosion is always a site specific decision.

The evaluation of forces causing bank erosion establishes the relative importance of factors causing erosion and the relative magnitude of the bank erosion problems for different river conditions. Utilizing the observed data at 103 erosion sites, a classification of causes of bank erosion in the Connecticut River was made by Simons, Andrew, Li, and Alawady ("Connecticut River Streambank Erosion Study, Massachusetts, New Hampshire and Vermont"). The relative importance of the major causes of bank erosion arranged in decreasing importance are: Shear stress (velocity), pool fluctuation, boat waves, gravitational forces, seepage forces, stage variation, wind wave, ice, flood variation, and freeze-thaw. Overall the predominant force causing bank erosion is the shear stress (or velocity). The effect of boat-generated waves on bank erosion is equivalent to about 10% of that induced by shear stress.

Another way to more clearly focus on the major causes of bank erosion is to subdivide these forces in relationship to where they act. The forces acting on the bank can be broken into two categories: (1) these forces that act at and near the surface of the water associated with pool fluctuations, related piping, groundwater, wind waves (generated by boat except when boat moves very close to

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the bank), ice and so forth, and (2) those forces acting
on the full height of the submerged bank (mainly velocity
or tractive force).

Assume a channel cross section as indicated in Figure
VI-A and further assume that the bank line is subjected to
forces generated by pool fluctuations, boat waves, wind
waves, surges, inflow of groundwater, and so forth. The
action of these forces near the surface of the flow causes
some erosion on the banks and may induce piping in lenses
of noncohesive material located in the upper part of the
submerged bank. If these were the only forces to which
the bankline was subjected, the bank would gradually adjust
by developing a shelf or a platform area wide enough to
dissipate the forces causing erosion, increasing upper bank
stability as the adjustment occurs (see Cross Section 2 in
Figure VI-A). The extent of this erosion landward would
in most cases be limited to an average of 10' to 15' in a
large river.

With flood events, high velocity flows are produced
which act on the full height of the submerged bank. This
force acts with a maximum magnitude at a distance about
two-thirds of the depth below the water surface. With
this maximum force being submerged a considerable distance
below the water surface, erosion of the total bank occurs
and the major bank line moves landward. This may result
in the total loss of bank material and the development of
a new channel geometry (see Section 3 in Figure VI-A).
This magnitude of erosion induced a shear flow is quite
often much greater than that caused by the forces acting
near the water surface.

(g) Principle of
     Lateral
     Differential in
     Water Level

The third dimension in channel geometry provides a
significant influence on channel configurations and the
effectiveness of river training structures. This dimen-
sion is provided by a principle developed by John J. Franco
(43, 44). It is his opinion that the third dimension will
have to be included in math models before they can be used
successfully in the solution of many local problems in the

Figure VI-A

Progressive Bank Erosion at Erodible Sites
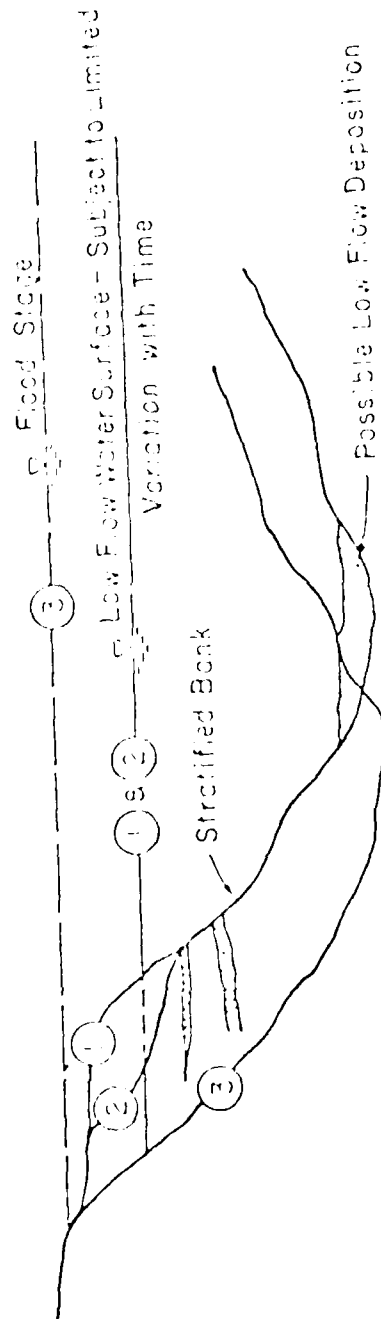
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design of training structures. The principle of lateral differential in water level is explained by Franco in the following paragraphs.

"When conditions are such that a lateral differential in water level or transverse slope exists or is produced by changes, there will be a tendency for some of the total flow to move toward the lower level; the slower moving, sediment-laden bottom currents can make the change in direction easier than the faster moving surface currents and account for the greater concentration of sediment moving toward the lower elevation." This principle is involved in many of the developments in alluvial streams including the formation of sandbars on the convex side of bends, movement of sediment around the ends and deposition behind dikes, development of cutoffs and divided channels, shoaling in lock approaches and harbor entrances, etc. In each case, there is either a buildup or reduction in water level on one side caused by centrifugal force, flow from tributary streams, channel enlargement or contraction, or flow diversion that results in a change in direction of at least some of the flow. Eddies are indications of lateral differences in water level."

"Water-surface elevations are usually measured along the banks of a stream and would not necessarily indicate local lateral differences in water level. However, the existence of lateral differences and some indication of the magnitude can be determined by considering the principal currents as beams of light of varying intensity (based on velocity) casting shadows in areas where lower water levels would be expected. Lower water levels would be expected on the convex side of bends, downstream of obstructions such as dikes or embankments extending into the channel, bridge piers, snags, or sandbars."

"The meandering characteristics of alluvial stream have to ve a function of the lter differential in water level. In a straight channel where there is movement and deposition of sediment, there will be a tendency for the channel to develop meanders because of lateral differential in water level that could be caused initially by uneven distribution of flow and sediment movement, differences in the roughness of the bed and bands, wind, and/or rotation of the earth. The difference in the water level will

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cause deepening of the channel on one side and deposition on the other starting a series of action and reactions and development of alternate bends. The size and shape of the meander pattern will depend on many factors, including discharge, erolibility of the bed and banks, valley and channel slopes and amount of sediment movement."

CURRENT TENDS IN RIVER
TRAINING TECHNOLOGY

While there are numerous regional (District) differences in technological approaches to river training which will be outlined in the following sub-section, there are, nonetheless, certain trends that can be summarized. Specifically, river training components including dikes, revetments, and cutoffs have been assessed according to the following components: design, construction techniques, construction materials, dike orientation, dike spacing, maintenance, cost effectiveness.

(a) Dikes

There are several possible dike designs (Figure VI-B) and they are often identified by varying terminology. However, all dikes may be grouped into the following general categories.

Spur Dikes: The most common type of structure used in channel improvement and development extends from the river bank channelward in a direction approximately normal to the channel being developed more and are generally referred to as spur dikes. However, these dikes have also been referred to as transverse dikes, cross dikes wing dams, jetties, etc. Spur dikes are usually included in a system of two or more. It is recommended that spur dikes be designed to provide a favorable lateral diffrential in water level.

Longitudinal Dikes: Longitudinal dikes are continuous structures extending from the bank toward the downstream generally parallel to the alignment of the channel being developed. These structures can be used to reduce the curvature of sharp bends and to provide transitions with little resistance or disturbance to flow. Little or no natural deposition can be expected landward of the dikes but the area could be used for the placement of dredged

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Figure VI-B

Types of Dikes in General Use
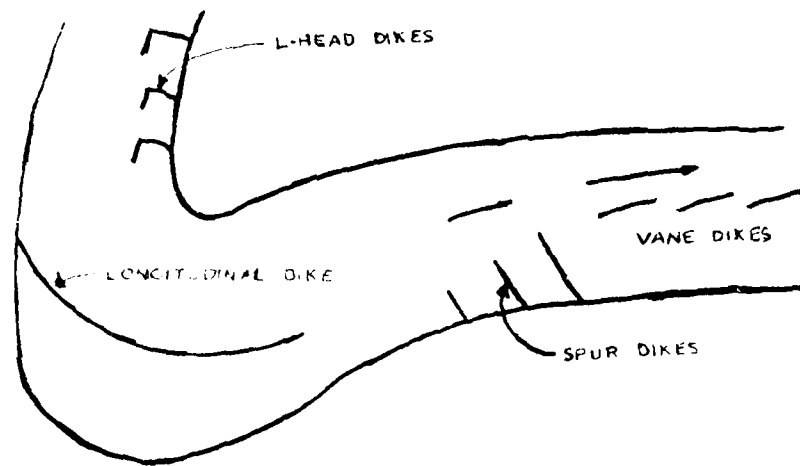
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material. Longitudinal dikes are considered the most effective type of structure when properly designed but are also the most expensive.

Vane dikes: Dikes placed in the form of a series of vanes have proved effective as a means of controlling channel development and sediment movement under certain conditions. These dikes consist of lengths of dikes located out from the bank with space in between and placed at a slight angle to the alignment of the current to develop the lateral differential in water level desired. The length of the gaps between the dikes is usually about 50 to 60% of the length of each vane and should be placed where there is or will be movement of sediment. These dikes developed as a result of model studies have been used successfully on the Mississippi and Arkansas Rivers. Vane dikes can be used independently or as extension to spur dike systems. Since vane dikes can be placed in relatively shallow water generally parallel to the channel limit line and produce little disturbance to flow they are much less expensive to construct.

L-Head Dikes: L-Head dikes re spur dikes with a section extending downstream from the channel ends generally parallel to the channel line. The L-Head section can be used when the spacing between dikes is too great, to reduce scour on the end of the spur dike, or to extend the spur dike system farther downstream. L-Heads tend to block the movement of sediment behind the dike and when the crest is lower than the main dike would permit surface currents over its top and cause scour on the landward side. These dikes could be designed to reduce shoaling in harbor entrances or to maintain an opening in the lower end of a bypassed channel.

1. Design. Types of structures used and their arrangements should be based on the characteristics of the stream, problem or problems to be resolved, and conditions contributing to the problem. The design of the structures should consider the effects of the structures on current existing in the reach and on movement of sediment and the effects of the resulting current on navigation.

There are several significant elements in the design of individual dikes. Of particular importance is the structure height in relation to the normal water

surface fluctuation zone. The Missouri Division, as indicated earlier, specifies a certain percentage of flow to pass over the dike thus providing a measure of equality on the impact of the river training system. The LMVD has established a similar approach by setting dike heights in reference to the LWRP for specific reaches. For other rivers flood conveyance or land reclamation may dictate dike heights which may rule out the use of the construction reference plane concept.

Both sloping and flat crested dikes are employed depending on the District. Generally, flat crested dikes are considered best suited for larger rivers where the dikes occupies a relatively small percentage of the cross sectional area. Flat crested dikes on small rivers tend to allow sudden changes in channel geometry when river stages first rise above the crest height of the dike. Sloping dikes tends to provide a transition as stages change and avoid abrupt changes which could affect the flow conditions. Model tests of the relative merits of the various dike designs have not been completed sufficiently to allow a conclusive decision.

The length of a dike is a function of the specific geometry of the reach in question and the authorized dimensions of the channel. In the Missouri Division, sills (underwater extensions of the dikes) have been added in recent years in order to create a more stable thalweg location.

2. Dike Spacing. The distance between adjacent dike structures again is not determined by an accepted formula. A rule of thumb suggests that the spacing is about one and one half times the dike length. The bend radius is a consideration in dike spacing. In general, the sharper the bend, the wider the dike system spacing, with the largest spacing in the central convex segment of the bendway. On may waterways, particularly the Missouri River Division, previously constructed dikes have existed for many years and presentdike spacing is necessarily determined by considering the effects of the older structures.

Model studies, according to LFranco (45), have been utilized to investigate the effectiveness of a stepped-up and stepped-down dike system. The stepped concept proposes varying the heights of the dikes in a system on a graduated basis in either an upstream or

downstream direction. While field data is needed before laboratory results can firmly be approved, the study concluded that stepped-down dike systems are more effective. Further, dikes constructed with their crests level with respect to each other are more effective than dikes having the stepped effect.

3. Dike Orientation to Flow. Generally, dikes are constructed at right angles to the bank or angled downstream from 7 to 22 degrees. This angle is based more on the estimated shap and general location of the end scour hole than any other parameter. On waterways that have an annual ice flow period or heavy debris from tirbutaries the downstream offer more resistance to localized flow.

Model studies have concluded that level-crest dikes should be placed normal to the flow or angled downstream. Sloping crest dikes should be placed normal or angled upstream. There is a greater tendency for dikes angled downstream to be flanked near the bank end than dikes angled upstream, and for level-crest dikes to be flanked near bank end than sloping-crest dikes. Exceptions have been noted, primarily in the Missouri River Division, where failure of upstream angled tends to be at the bank end.

4. Construction Materials. The availability and resulting cost of materials has generally dictated the selection of materials for dike construction. Historically, low labor dosts and timber tended to dictate the use of pile clumps as dikes. Presently, stone is the most common construction material although exceptions, such as the Pacific Northwest which still uses timber pilings, do exist.

The advantages of stone are listed as follows: (1) Stone is the least expensive construction material if quarries are located near the river (2) Stone can displace to conform to bed scour without total structure failure before repairs can be accomplished, (3) Stone can be salvaged and used at other locations should the need arise, (4) In cold regions with ice stone is more resistant to ice pressures, (5) Minimum labor requirements allows reduced construction costs.

The quality, size range, and rock type will necessarily be dependent upon local availability and varies considerably between regions. Limestone, for example, may be

subject to breakdown, especially in regions with ice. In the Missouri Division 500 pound stones have been reduced to 50 pound pieces within a few years. Quartizite stone on the other hand has been found to be almost maintenance free.

     5. Construction Technique. Construction of dikes may be either a land plant type or floating or a combination of the two. If the dike dimensions warrant a width sufficient for truck hauling and if there are low rock supply sources and low water conditions exist the land plant system is possible. Generally, however, the floating type plant is preferred because of reduced costs. When dikes are used to move the thalweg a considerable distance or constrict a very wide channel, the dike is lengthened in phases to allow the river to adjust to the new conditions.

     6. Maintenance. Maintenance requirements are most site specific in their occurrence. During the initial years after construction there appears to be a seasoning period beyond which stone dike maintenance is significantly reduced. Very high floods or ice can, of course, greatly increase the need for maintenance. Estimates from the LMVD suggest that only about 2% of the expenses for the dike and revetment construction program is required for maintenance. This percentage should be used with caution as it is highly variable depending on the particular site conditions.

     The location and exposure of dikes often determines the amount of maintenance required. The most critical location for dikes, because of strong flow attack pressures, is along the off channel side in crossing areas. This is especially true when during high flows the thalweg shifts closer to the dike and scours deeper holes at the structure ends. Repairs at these locations are bound to be the most frequent and also are critical to the proper functioning of the dike.

     Flood flows which overtop the dike cause elevation degradation by scour and build-up of floating debris. Strong eddy currents develop along the bankline and can cause failure at the dike root section. Once the dike is flanked by erosion through the root area, a strong landward erosion will continue for the duration of the flood flow. Higher flows which only overtop the structure crown one to two feet will deposit large amounts of sediment

within the dike field and these fill elevations will equal or slightly exceed the dike crown elevation. This filling action adds strength to the dike system and, in turn, reduces the structure's vulnerability for the more severe floods.

The Fish and Wildlife interests have expressed concern over excessive fill behind dikes as the water area available for fisheries is naturally reduced. In some locations notches have been constructed to maintain habitats behind the dikes. In the Missouri Division a policy has been established whereby some damaged dikes have not been repaired in order to allow the notch to serve the fisheries interests. Another important factor in limiting fill behind dikes has been the lowering of dike crests to near the normal water surface.

The costs of dike construction very significantly according to location. Local labor costs, material availability, accessibility and transportation are all factors that determine the total costs. Cost estimates are usually made according to river mileage location and the anticipated difficulty of placement. As an example of dike construction costs in the LMVD the present range is from $5 to $12 per ton of stone in place. In recent years, the cost of dike construction, which is primarily a function of transportation cost has risen significantly and is expected to continue this rise in the near future.

(b) Revetments and
    Bank Protection

Streambank erosion has historically been a major concern in the United States of America because of serious economic losses to both private and public interests located adjacent to these streambanks. However, the conclusion of WES report by Keown (46) stated that the state of the art of streambank protection has not advanced significantly since 1950. Much of the revetment and bank stabilization projects have been characterized as a "band aid" approach which attempt to control areas subjected to active bank erosion. It has been considered good engineering practice to solve each bank protection problem independently since streambank erosion problems and hydraulic conditions vary significantly between locations. Previous studies by international reachers have not produced specific guidelines for bank protection but rather the

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engineering community has adopted a group of methods that
are extensively accepted.

      1. Bank Protection Methods. The most widely
used bank protection methods associated with navigation
channel at the present time include the following:
a) Stone riprap, b) Concrete pavement, c) Articulated
concrete mattresses, d) Transverse dikes, e) Asphalt
mix, f) vegetation, g) Gabions or rock sausage, and
h) Bulkheads.

      As was pointed out in the section on dike con-
struction stone riprap is widely used because of its
availability, durability, and low labor requirements. The
effectiveness of riprap varies to a large degree because
of its placement and gradation. Both quarry run and
graded stone are used for riprap placement. The minimum
stone size may be determined using empirical relations as
a function of maximum hydraulic flow occuring along the
bank. Failure of riprap because of piping during reverse
flow periods has led to recommendations that a protective
filter is needed between the rock and the bank in in-
stances where sufficient fine filter material is not
incorporated within the specified stone gradations. The
majority of theoretical design work related to streambank
protection works has been directed toward riprap but no
established design procedure has been advocated.

      Articulated concrete mattresses are employed
extensively in the LMVD and were described earlier. This
process is unique to LMVD because of the construction
plant requirements. The remaining methods are used much
less extensively and are briefly described in the follow-
ing paragraphs.

      Concrete pavement is expensive and is used only
where high capital investments around industrialized,
heavily populated areas, bridge abutments, or main line
levees are located. This method resists deterioration but
scour under the slabs and inadequate subsurface drainage
may cause problems.

      Transverse dikes are used as a bank protection
measure as well as in improving channel requirements for
navigation. The dikes are designed in the same manner as
described under the dike section. Their function is to
deflect or direct the eroding currents away from the bank
and, as such, the dikes alignment is often quite varied.

Asphalt mix has been employed in a similar manner as concrete mattresses. The asphalt mix was poured directly on to graded surfaces but its inflexibility and the high cost of petroleum products have significantly reduced its use.

There is an increasing trend in the use of vegetation as a bank stabilization measure. Both grass and woody vegetation have been found effective in certain situations. Species selection is, of course, site specific and such factors as length of growing season and the incidence of prolonged periods of submergence are critical factors. The advantages include low cost and providing an aesthetically pleasing appearance.

Gabions are rock filled cages that have been utilized in Europe for many years but have been widely used in the United States for only the past 18 years. The wire mesh of the cage is galvanized steel. The gabions are somewhat flexible and allow bank drainage but are expensive.

Bulkheads are typically used in areas with high traffic across a water-land interface. Bulkheads are made from any number of products, usually based on availability of material, including timber, concrete, and prefabricated asbestos fiber or aluminum. The high cost of this method requires that it be used in developed areas requiring assured protection such as marinas or other waterfront locations.

2. Construction and Costs. A summary of 1976 costs for streambank protection methods was provided by Keown et. al. and is shown in Table VI-1. The 1980 costs for articulated concrete mattresses in the LMVD has been estimated at $130 per 100' for a 550,000 square program. The latter cost varies with the size of the program but includes all grading, paving, transportation, labor and material.

3. Stream Bank Erosion Control Act. The passage of the "Streambank Erosion Control Evaluation and Demonstration Act," of 1974 underlined the concern with erosion losses and promised an opportunity to gain new insights into streambank erosion protection schemes. The program includes the evaluation and monitoring of existing projects, laboratory testing of new concepts, and the field testing of new techniques. Specific emphasis has been

Table VI-1

1976 In-Place Cost* Summary for the
Streambank Protection Methods

Streambank Protection Method	Cost/Unit, $	Unit
Stone riprap	3.50-30.00	yd^3
Concrete pavment	90-125	100 ft^2
Articulated concrete mattresses	84	100 ft^2
Transverse dikes:		
Pile board	40-55	lin ft
Untreated clumps	1500-2300	clump (three 60-ft piles)
Stone	40-65	lin ft
Fences	25-50**	lin ft
Asphalt mix (upper bank)	60-80	yd^3
Kellner jack field	16-47***	lin ft
Vegetation (grass)	1.15-1.49 (500-650)	100 ft^2 (acre)
Gabions	40-47	yd^3
Erosion-control	5.56-722 (0.50-0.65)	100 ft^2 (yd^2)
Bulkheads	14-105	lin ft

*Cost figures supplied by Corps of Engineers divisions and districts.

**Range applies to new materials.

***Range applies to used and new materials.

placed on effective, low cost measures which incorporate
environmental objectives in their design.

In order to develop methods of controlling stream
bank erosion, it is emphasized that the specific causes
must be identified. The basic mechanisms of bank erosion
were outlined earlier but continued efforts are underway.
Initial emphasis have been placed on an extensive liter-
ature survey of known causes of streambank erosion and
protection methods.

Hagerty (47) in his studies on the Ohio River
found that while the dominant bank failure occured as
expected during flood stages and during drawdown after
high stages there were also many instances of unexpected
caving. The locations of much bank caving were unexpected
in relation to geographic location and time occurence. In
each case specific reconnaissance to the site was neces-
sary to determine the contributing factors to the bank
failures. Hagerty concluded that bank erosion on the Ohio
River was not caused to a significant degree by lock and
dam operation or by operation of commercial or recrea-
tional craft. Rather land use was found to be a signif-
icant factor particularly when changes in the application
of water to land adjacent to the river banks was involved.

(c) Cutoffs

Cutoffs are designed to eliminate sharp bends, elimi-
nate troublesome reaches with high dredging requirements,
reduce the length of the navigation channel, or increase
the flood carrying capacity of the river. By far the most
significant use of cutoffs was on the Lower Mississippi
River between 1929 and 1942. During that time the River
was shortened a distance of 151.9 miles from both manmade
and naturally occurring cutoffs. Since 1939, an addi-
tional 54 miles has been subtracted from the rivers length
by chute cutoffs. The effectiveness of cutoffs has been
periodically questioned throughout the history of the
Mississippi River and in recent years the construction of
cutoffs has become infrequent.

There are two types of cutoffs, the neck cutoff and
the chute cutoff. The neck cutoff is developed by cutting
a channel across the narrowest portion of a meander loop
thus producing an oxbow lake. A chute cutoff is developed

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by cutting through a point bar usually in the path of the shallow channel which exists during high states.

Since 1942, there have been no neck cutoffs on the Mississippi River although there have been 40 chute cutoffs constructed. Attempts were made to develop more chutes but were finally abandoned. Many of the abandoned attempts are presently divided reaches which cause navigation problems and extensive dredging.

Some problems associated with divided reaches have been solved by the technique of branch closures. Branch closures are accomplished by constructing one or more dikes, usually at the upstream entrance of a branch channel. The flow is thus concentrated through the remaining channel and navigation depths are often improved.

While cutoffs on the Mississippi River are not presently contemplated, other rivers, which have recently been developed for navigation such as the Arkansas and rivers presently under construction such as the Red and Tombigbee, do incorporate cutoffs in their development. The technique of constructing cutoffs is straight forward. After selecting the alignment for the cutoff pilot channel, the right-of-way is cleared of vegetation. The pilot channel is then excavated by dredges to a depth equal to the natural river channel but dependent upon the character of the subsoil along the cut. It is necessary to excavate the bottom grade of the cut below any clay lenses or other non erodible sediments until the erodible sands of the flood plain are reached.

The size, slope, and alignment of the pilot cut is accomplished such that the cutoff will develop naturally to take most or all of the flow of the stream. The rate of development of a cutoff depends on the erodibility of the material through which the cutoff is made, size and shape of the pilot cut, length of the cutoff with respect to length of the channel around the bend, and location of the entrance with respect to the alignment of the existing channel. The rate of development of a cutoff can be increased by the gradual closure of the old bendway channel or by structures designed to increase the tendency for

shoaling in the upper end of the existing bend and to
direct flow toward the pilot cut.

In recent years, emphasis has been placed on maintain-
ing the oxbows for recreation, harbors, and fish wildlife
considerations by keeping the oxbows open to the river.
In many river reaches the oxbows are the only locations
where these activities are possible.

In constructing the cutoffs to produce the oxbow lakes
the general practice is to close off tne upper end of the
old bend with a closure dike or embankment to eliminate
the movement and deposition of sediment in the bend.
Structures will usually be required in the lower end of
the old bend to reduce the tendency for shoaling and the
need for maintenance dredging.

EFFECTIVENESS OF RIVER
TRAINING

An assessment of the effectiveness of river training
is provided with emphasis on the impacts of river training
on river morphology, tradeoffs between river training and
dredging, the relationship between the amount of river
training and dredging and the costs of river training.

    (a)   Short and Long
           Term Impacts of
           River Training
           on River
           Morphology

River channels exhibit great variability in channel
dimensions including cross-sectional area, width-depth
ratios, slope of energy gradient, bank and bed-material
characteristics, bed forms, bar locations, channel align-
ment, etc. This variability plays a very significant role
relating to sediment transport, the position of channel
thalweg, bank stability, and navigation depths. Wide
shallow reaches, broad bends, and divided flow reaches
encourage sediment deposition and are usually located
where significant dredging and river training works may be
required to maintain te hydraulic effectiveness of the
channel for flood control and navigation. Also, many

reaches of rivers may have a poor alignment regarding
channel stability and navigation. To correct the river
alignment revetment, diking, and cutoffs are usually
utilized.

As described previously river training works include
one or more combinations of bank stabilization works,
dikes, and cutoffs. Bank revetment stabilizes the banks
limiting further erosion and in turn reduces the sediment
supply originally derived from bank erosion. Therefore,
the impact of bank stabilization on river morphology may
be localized as far as major changes in sediment supply
are concerned.

Utilization of dike fields to change the channel
alignment and reduce the channel width has a more profound
effect on the river morphology than that induced by bank
stabilization. The river bed usually aggrades upstream of
the dike field. Backwater effects caused by the dikes
decrease the velocity and increase river stage for a sig-
nificant distance upstream of dikes. This reduces the
sediment transport ability of that reach of river encour-
aging deposition. However, this effect may diminish with
time when the riverbed in the diked river section degrades
lowering its stage. Degradation initiated here may propa-
gate upstream to affect the system upstream of dikes.

In the main channel along the dike field the river
width is reduced and the velocity as well as sediment
transport ability is increased. This causes general
degradation in this reach of main channel and increases
the navigation depths. However, within the dike field
sediment deposits may be stabilized by growth of trees and
willows. The tree and willow growth encourages additional
deposition whenever the area is flooded. In most cases
the ultimate effect of a high dike field is to cause the
river to develop a new bankline at the extremity of the
dike field. This reduces channel width and may reduce
channel capacity. The effects of dike construction on the
river morphology in the Mississippi River between river
mile 140 to 154 is a good example. According to the Corps
waterways experiment staion Technical Report Y-74-2, in
1937 this river section was 3,700 feet wide and had an
average depth of 30 feet deep at bankfull stage. The
dikes started in the 1830's and completed before 1888

decreased the width permanently to 2,100'. In 1973, the average depth prior to the 1973 flood was about 45 feet at bankfull stage and the width-to-depth ratio has decreased from 123 to 47.

Downstream of the dike field the riverbed will aggrade after construction of dikes because of the increase in incoming sediment caused by the channel contraction in the diked river section. However, such effect will be short term. With the diked river section reaching an equilibrium the aggraded riverbed downstream of dikes will then slowly degrade to approach the original bed elevation prior to dike construction.

Because the combined effects of over contraction caused by dikes in the river channel and construction of levees on the flood plain, the water stages may become lower at low flow and higher at high flow as compared to natural river conditions.

The effects of neck cutoffs and chute cutoffs on river morphology are somewhat different. Neck cutoffs result in much steeper local gradients than existed in the original channel, and thus these cutoffs may develop and transport a major portion of the river discharge. This causes their channel beds to degrade. The old channels as a consequence of these activities, may be subjected to sedimentation problems. If the islands separating cutoffs from old river channels are heavily vegetated, this vegetation may trap sediment and allow clearer water (carrying less sediment) to enter the old river during periods of overbank flow to the old channel. In this case, the upstream end of the old river usually silts up blocking further sediment from entering from the main channel and thus the old river may remain biologically stable for a relatively long time. The long-term response of a river to cutoffs is often a period of instability, with potential for considerable bank erosion and lateral shifting if banks of cutoffs are not protected.

Chute cutoffs usually share water flow with the main channel at flood stage. Therefore, water velocity in the chutes might be insufficient to transport sediment through the system. This can result in silting in the chute as

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well as in the main river channel requiring dredging of the main channel to meet navigation requirements. To avoid further deterioration of the main channel special treatment may be required.

General criteria to maintain active side channels that may be important biologically and for recreation are:

If the side channel is isolated from the main channel by large heavily vegetated islands and a dike (artificially built or natural), the side channel becomes partly isolated from the main sediment discharge on the river causing it to have a relative-long life.

It is possible to realign the entrance to a side channel so that the intake limits entrance of sediment to the side channel.

Generally speaking, the life of side channels will be increased if their intakes are closed soon after the cut-offs form. Man-made low head dams may be used to close the intakes.

> (b) Possible
> Methodologies
> for Tradeoffs
> Between
> Dredging and
> River Training

By properly combining the use of dikes, bank revetment, and overdredging, it is possible to reduce dredging frequencies, avoid problems associated with environmentally sensitive areas, and still maintain or even reduce dredging requirements. The difference resulting from utilizing dikes versus overdredging is that the dikes can reduce the dredging requirements at the diked river section but may increase dredging requirements downstream of the problem area, while overdredging may have adverse effects resulting from the production of large quantities of dredged material at a particular point in time. To develop some guidelines for establishing a practical and environmentally justified dredging program, a water and

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sediment routing model can be applied to evaluate differ-
ent combinations of dikes and overdredging. This type of
analysis shows that if there are a number of dredging
sites close to each other, overdepth dredging of the up-
stream dredging site can significantly reduce required
dredging frequency and yet not increase the total dredging
requirement; overdredging of a site where other dredging
sites are not located immmediately downstream is not
recommended; diking of a site where no other dredging
sites are located immediately downstream can reduce the
dredging frequency and possibly the total dredged quanti-
ties at least for a short term; diking of a site located
upstream of a number of dredging sites is not recom-
mended. To avoid dredging of a site, either overdredging
its upstream section or diking the site are possible
solutions.

(c) The Relation-
     ship Between
     Volume of
     Dredging and
     River Training

Dredging is a temporary but necessary solution to the
problem of maintaining navigable depths in many reaches of
rivers. In general, wide shallow reaches, broad bends and
divided flow reaches are sites that require significant
and possibly frequent dredging. It is possible to train
the river mainly by using dikes and bank revetment to in-
crease the water discharge per unit of width, redistribute
sediment, and thus reduce the adverse impacts of wide
shallow areas that may require frequent dredging. How-
ever, it is also recognized that unless the sediment sup-
plied into the river can be reduced at its sources a cer-
tain level of dredging is necessary.

The effect of river training on dredging requirements
appears to be significant. Rivers with a high degree of
control over discharge because of reservoir operations
have reduced dredge requirements practically to zero. The
Missouri and Arkansas Rivers are notable examples in this
category.

The Lower Mississippi River, as a result of training
works, has reduced the number of dredging sites from 65

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locations in 1955 to only five in 1979. The total volume of dredge material has not changed significantly in spite of the concentration of dredging sites. It is believed by Corps engineers, however, that in recent years training works are beginning to show a more noticeable effect and that dredging volumes will be decreased in the future. It should also be noted that the reliability of maintaining depths of nine feet and above has increased markedly since the river training program was begun.

Authorization has been granted, although funding has not yet been provided to adopt a 12 foot channel in the LMVD because of the increasing reliability of channel depths. It is estimated, however, that should the 12 foot channel be adopted in the near future then dredging volumes would be increased above present levels.

Protection of severely eroded banks is a positive way to reduce dredging requirements. However, because bank erosion supplies a small portion of total sediment load entering the river system, the effect of bank protection without contraction on dredging quantities is minor. Construction of dikes may only change the dredging location but not the total dredging quantity. Even if there is a reduction in dredging requirements in the diked river section, the dredging requirements downstream of the diked section may increase. This emphasizes the importance of analyzing the system versus utilizing a reach approach.

In general, considering the environmental constraints and dredging costs, it is usually more realistic to use river training works to reduce the number of dredging sites and dredging frequencies rather than to reduce the total dredging quantities by management of watersheds and tributaries. By properly using dikes it is possible to eliminate dredging at environmentally sensitive areas where dredging and disposal operations are not permissible. Also, by considering overdredging, time of dredging, location of dredging and channel improvement, the total dredging and frequency of dredging can often be reduced.

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(d) Costs of River
     River Training

The costs of river training are not quantifiable in
terms associated solely with benefits to navigation.
River training provides benefits not only to navigation
but also to flood control, stream bank protection, and
actual land creation in some cases. For example, cutoffs
and revetment works on the Mississippi probably provide
more benefits to flood control than all other project'
purposes combined. In the Missouri River Basin large
areas of agricultural land have been created behind dikes
which were constructed specifically for that effect. The
benefits which accrue to such purposes are not separated
but are determined under the broad heading of "channel
improvement."

The river training systems are almost complete in the
Lower Mississippi and Missouri basins. Therefore, the
capital expenditures for river training works on these
rivers provide examples of costs associated with channel
improvement. The total expenditure of river training
works in the Missouri River Division over the life of the
project has been $430 million or $589,000/mile for the 735
mile length of the project. The effect on navigation of
these works has been a stabilized channel with the prac-
tical elimination of dredging. It should be noted, of
course, that flow regulation from upstream reservoirs also
contributes to the success of the river training
structures.

On the Lower Mississippi River a total of $1.1 billion
or $1.2 million/mile has been spent in the LMVD on river
training works over the 761 river miles. It is estimated
that the training works are about 76% complete in the LWVD
with the greatest percentage of work remaining in the New
Orleans District. The costs associated with the revetment
program are, by far, the largest costs as compared to tike
and cutoff construction. In recent years, the cost of
revetment has risen steeply and is expected to continue to
rise in the near future. In 1976, articulated concrete
mattresses cost $100 while 1980 costs are at $130 per 100
square feet. The per mile costs will be higher in the
future also because of the dominance of work remaining in
the New Orleans District where channel depths require more
revetment works. In Memphis District revetment works

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require two to three squares per foot, Vicksburg District requires three to four squares per foot. At current prices of $125 per square the cost of revetment per mile will be $3.3 to 4.0 million per mile in the New Orleans area. The current technology of river training adopted in the Lower Mississippi has proved to be successful and no major changes is expected before the end of the project.

EXPERIENCE IN RIVER
TRAINING METHODS

(a) United States
Regional
Experience

The complexity and scale of river mechanics has, to date, defied the development of practical solutions to river problems. Several papers on the subject of river training have indicated that the types of training works used and the procedures applied have, historically and are presently, still a matter of experience and general judgment. While such a trial and error approach has produced many failures there is, nonetheless, some established criteria for the installation of training structures. As mentioned earlier these structures are generally specific to a particular reach of river. The salient features of river training, both presently utilized and expected to continue in the future, are therefore presented on a river segment basis which generally corresponds to Corps districts. For a review of the terminology and description of the various structures utilized in river training the reader is referred to previous sections.

1. Lower Mississippi River. River training works are constructed on the Lower Mississippi which produce benefits to both flood control and navigation. A channel stabilization master plan developed in 1956 and periodically updated has outlined all training works on the LMVD and complete revetment of river banks from Baton Rouge to New Orleans is presently about 76% complete. The deep channel precludes the use of dikes in the New Orleans District. In the Vicksburg and Memphis Districts revetment an dike construction is proceeding on a site specific basis. No cutoffs are contemplated in the near future.

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Presently, and expected to continue in the future, revetment works utilize articulated concrete mattresses with stone paving.

The placement of the mattresses begins with the grading of river banks to a stable slope. The grading extends from the top of the bank to from 15 feet to 20 feet below the surface of the water which is the limit of good control of the grading equipment under water. Near Baton Rouge, where the low water currents are milder, grading is extended to the 30 foot depth with fairly good control. Clearing of the bank and snagging of the underwater area to be covered by the mattress precedes grading. The mattress is cast in 4-ft. by 25-ft. units called "squares" consisting of 20 slabs, each 3 ft. 10-1/4 in. long, 14 in. wide, and 3 in. thick space approximately one inch apart of heavy erosion-resistant reinforcing fabric. This work is done at several casting fields located at strategic points along the river, and is accomplished by contract. The scale of work involved has required the existence of several fabricating plants whose work load has been assured for decades. The engineering objective is to provide sufficient bond-to-fabric to permit transportation, fabrication, and launching without excessive breakage. Great compressive or tensile strength is not required. When completed, the mattress extends from the water's edge to a point just riverward of the toe of the underwater slope.

The paving extends from the landward edge of the subaqueous mattress to the top of the graded bank or to some previously determined elevation above the ALWP. The most common material used for paving is graded stone. The stone ranges from 6 to 125 pounds. Sand asphalt was formerly employed but high costs and a lack of effectiveness have precluded its use.

The design of dikes is site specific. The dike height is not determined by general criteria, and in the dike system, dikes may be stepped-up, stepped-down, or the same elevation. The dike profile is sloped over the entire length with the first 200 to 300   : coming from the top bank elevation to approximate' ⁄   -bank height. The stream end is usually 7 to 12 fe. ⁻ᵇᵘᵗ⁻ the existing channel bottom with an end slope as ᵥₐₐt as 1V on 10H. The dike spacing is a function of the river alignment and the dike length is, in turn, a function of the existing top bank width. The dike angle is determined so that the

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bank end is perpendicular to the bankline and the stream end is perpendicular to the flow. Therefore, the dike is not necessarily straight, but sometimes of changing alignment although the actual relation between the bank and flow varies with stage.

Dikes are normally constructed in stages of three possible types: vertical stages on individual dikes in one construction season; construction of the dike system starting with the upstream dike; and vertical stage construction over a period of years to allow sedimentation within the dike field. Graded stone A which may weigh up to 5000 pounds is the primary construction material on all stone dikes.

2. Middle Mississippi River. In the St. Louis District revetment is constructed with grades stone. The minimum thickness is 18 inches of grade C stone which may weigh up to 400 pounds. The stone is placed by ship, clamshell or other approved methods which largely depend on accessibility.

The construction of dikes is determined by a concept termed "degree of contraction." The contraction is the distance from the river end of a dike to the opposite bank or dike end to dike end. A prototype study reach from mile 140 to mile 154 above Cairo, Illinois, was completed in 1969 to determine the effect of contraction. By building new dikes and extending existing dikes, the channel width has been decreased from 1800 to 1200 feet. The new dikes have a uniform sloping crest profile while existing dikes have only the extension sloping. The dikes are normal to the flow or angled downstream, have 200 feet of revetment downstream, and are constructed in a stepped-down arrangement. It was found in the past that dikes with level crest profiles cause scour downstream of the dike at the bank; therefore, any dike having a level profile now has a 300 foot section sloping from the top bank to the design level crest elevation.

Dike notches have also been constructed in the District to improve fisheries habitat. The notches were either designed into new dikes or were left during the raising of a dike. Both "vee" and trapezoidal notches approximately six feet deep have been constructed.

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3. Upper Mississippi River. In contrast to the
Middle Mississippi River, the Upper Mississippi river uti-
lizes a series of locks and dams supplemented by dredging
to maintain the navigation channel. The Upper Mississippi
carries a relatively small sediment load and has
relatively stable banks compared to the Middle Missis-
sippi. In the Rock Island District no dikes have been
built on the Mississippi River since 1948. The St. Paul
District is currently considering the use of groins and
dikes to reduce dredging and maintain a stable navigation
channel. Studies conducted by the University of Minnesota
at the St. Anthony Falls Hydraulic Laboratory and the
Colorado State University Engineering Research Center have
provided certain insights which the District will utilize
in future river training projects and in maintenance
dredging programs.

The model studies concluded that the final
selection of a dike configuration to be used is dependent
of factors other than just the ability of attaining pre-
scribed scour depth in the constricted region. For
example, consideration should be given to uniformity of
scour depth across the entire width of the constriction as
well as local scour around the tips of the dikes and
possible impacts on the river reaches upstream and down-
stream of the dikes. Of the dike types tested, it
appeared that the downstream angled dike was the most
efficient in this regard. Parallel wall constrictions
were alkso efficient, but construction costs may be ex-
cessive in the prototype.

Selection of the dike type and longitudinal
spacing of the dikes is also dependent on conditions
existing in the prototype, such as bends, water level, and
gradient. These conditions may require additional model
studies to assess the overall performance of high water
which may cause the dikes to become submerged.

4. Missouri River. In its original state, the
Missouri River was a multiple channel, heavily sediment
laden stream. Bank erosion was a major problem. Pro-
gressive river training structures and upstream reservoirs
have pressntly stabilized the river and dramatically
reduced flood stages and total sediment load.

The Missouri River Division has developed a
concept of dike construction which is based on a "Con-
struction Reference Plane" (CRP). The CRP is based on the

flow that is equal to or exceeded 75% of the time and
takes tributary flow into account as one moves down
river. Thus, during the 8-month navigation season, the
dikes referenced to the CRP act uniformly a system and
are, theoretically, overtopped the same number of days
each year.

As a result of the more than 1600 dikes con-
structed on the Missouri River, present channel widths
range from 600 feet at Sioux City to 1100 feet at the
Mississippi River confluence. The guidelines for dike
spacing from Sioux City to Rulo, Nebraska, is 600 to 800
feet, 600 to 1000 feet from Rulo to Kansas City, Missouri
and 800 to 1000 feet from Kansas City to the confluence.
Generally, dikes are farther apart on convex bends and
closer together in straight reaches. The spacing seems to
be a function of the radius of the bend since flatter
bends do not exert control over the flow and closer
spacing is required. When additional dikes were required
after the initial construction of a system, these spacing
guidelines were not strictly followed. The space avail-
able to obtain maximum efficiency of the channel flow,
accumulate sediment within the dike fields, and reclaim
land form the basis of dike spacing.

The orientation of dikes is generally at an angle
of 7 to 22 degrees downstream. Dikes cause strong eddy
currents which create large scour holes at the end of the
dikes. The shape of this scour hole and location of the
downstream deposit is related to the angle of the dike.
The more the dike is angled downstream, the more the scour
hole is aimed away from the dike. The submerged sill ex-
tensions to existing dikes are also utilized. Sills are
used to align adverse flow conditions which usually occur
on long, flat bends. The sills are constructed perpendic-
ular to the flow because (a) the amount of material and
therefore costs are reduced, (b) the overtopping flow
tends to streamline and (c) the downstream shoal can be
predicted. Sloping crests on sills are avoided since flow
lines are less uniform and turbulence is increased which
reduces the effectiveness of the structure.

Materials used for dike construction are
presently stone although some pilings used as mooring
clumps have also been required although they are presently
no longer used. The particular gradation is dependent on
the cost and availability of the stone. The crest profile
is generally level and the dike crest is above the water

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level 75% of the time. The side slopes are the natural angle of respose. To add strength to a dike, often the crest width of the dike will be increased. The advantages of stone dikes are: stone is generally available all along the river; since stone displaces verticallv, the dike tends to "heal" itself; there is a lower labor cost of construction; stone dikes withstand ice pressures; stone dikes tend to have a "seasoning period" where the maintenance decreased with time; in some instances it is possible to use stone agian; and stone dikes tend to attract fish.

Notches in dikes for improving the habitat of fish is also being actively pursued. The notches are obtained by three different methods: notches 20 to 50 feet wide and 2 to 5 feet below the CRP are excavated in existing dikes; when existing structures are raised or repaired, notches are left in them; or new structures are designed with notches. At present there are about 1000 notched dikes in the Division. There appears to be, however, some question as to the real effectiveness of the notches in increasing fish production although the Fish and Wildlife interests actively promote the notches.

During the past seven years there has also been a program of minimum maintenance established to further promote fisheries habitats. The program reevaluated the design channel widths and allowed the ends of dikes to deteriorate and the overall channel width to increase with no loss to the navigation channel width. In areas where no major damage is likely, revetment deteriorated from freeze-thaw has been allowed to fail to a limited degree. In dike fields on good radius bends with navigation problems, where the system has performed its function, or the dikes are too long, every other dike has been allowed to deteriorate. In some instances, only the stream end of the dike has been allowed to deteriorate. All of this is done so as to not adversely affect the required navigation channel.

5. Arkansas River. The Arkansas River, being the newest river system developed for navigation, benefitted from the experience gained in river training from other Corps District. Initially pile dikes were utilized similar to dikes employed on the Mississippi River, however, subsequent dikes were built of stone. Some of the design parameters of the stone dikes constructed during the project are (a) a crest elevation 16 feet above the

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Construction Reference Plane (CRP) which was determined for a discharge of 20,000 cfs, (b) bank paving 20 feet upstream and 200 feet downstreatm, and (c) dikes in a system constructed with the upstream dike first. Generally, there has been little maintenance on the project since being opened in 1970.

6. Apalachicola River. The Apalachicola River employs stone dikes which have superceded timber and stone filled timber dikes. The contraction width of the dikes is 500 feet on the upper parts of the river and 550 feet on the lower parts. The dikes have a sloping crest, the dike systems are stepped-down, and the dike spacing is one to one and a half times the dike length. A stone blanket 50 feet wide and constructed to the high water line is used as the base for timber and stone dikes. The dike effectiveness seems to be related to: the degree of contraction; the current patterns; the channel sinuosity; and the layout of the dike field. While the dikes have improved the overall condition of the river there are still problems with degradation and bank instability.

7. Alabama River. The Alabama River employs stone dikes which are spaced one to one and a half times the dike length, and the dike system stepped-down. The most downstream dike in a system is one foot above the low water profile and the most upstream dike in a system is angled downstream 45 degrees. The length of the dikes was selected to be 30 to 40% at the low water profile elevation. Some dikes have been constructed with a broken crest profile where the dike starts level at the bank end and drops in elevation to another level section. These dikes are constructed with a 12-inch stone blanket on the bank end and an 18-inch stone blanket on the stream end. It is considered that the dikes have not generally been effective because of poor quality construction and the flat river slope (0.1 foot/mile).

8. Columbia River. The Portland District is unique in that pile dikes are constructed of Douglas Fir timber. The pile dikes are constructed of Douglas Fir timber. The pile dikes are constructed in water as deep as 35 feet and have rock blankets on the stream and bank ends. This rock blanket is constructed with graded stone. Dikes are not constructed on the inside of a bend since, in contrast to other rivers, this tends to cause the opposite bank to erode.

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Stone dikes have not been built since 1900. Such structures caused the stream end to scour immediately and the entire dike was eventually lost due to settling.

The timber used for piles is untreated but caps and spreaders are used. Some of the piles are still in place after 100 years. No submerged dikes are built and the stream ends of the dikes are at least 250 feet from the navigation channel to reduce navigation hazards.

(b) Foreign Experience

Several concepts and devices have been developed outside of the United States that could potentially be useful in river training considerations.

1. Dominant Discharge. The Delft Hydraulics Laboratory, according to Van Berklekom (48), has promoted the concept of a "dominant discharge" theory. The theory was developed by NEDECO engineers as a result of their Niger River studies. Basically, the theory states that there exists within river systems a specific flow condition or "dominant discharge" that will produce a morphological equilibrium such that yearly scour and deposition total zero. This is considered the most efficient river profile just capable of complying with "natures instructions" which determines discharge (Q) sediment transport (Q_s) and sediment size (D) for a particular river. It is hypothesized that a river will strive for optimum use of its available energy which is to procduce maximum sediment transport for a given limited available energy. It appears that slope and widt will be adapted to an average Q, Q_s, and D; that depth (h) will oscillate around an average value; and that roughness (K_r) will vary according to flow conditions. The question then becomes to determine the average A, Q_s and D, and the oscillation of h when yearly scour and deposition total zero. This is achieved by plotting discharge against the following parameter:

$$K = \frac{nTp}{h\Delta h}$$

h = depth;
Δh= the interval on the h-scale;
n = the length of time during which the river
stage is within the interval concerned, i.e.,
ranges between h and h + h;
T = the transport capacity of the river when its
stage is in the interval concerned; and

$$P = {}^{1+} \left[\left| \frac{0.25}{T/bd3/2 \ \sqrt{\Delta g}} \right| \right]^{2/3}$$

A so called "K diagram" is thus produced and the
center of gravity of this plot thus indicates a represent-
ative condition or dominant discharge.

The apparent corrallary of this theory is that
river training efforts should strive to approach the
channel conditions associated with the dominant dis-
charge. Any changes significantly outside of this value
will produce a channel that is inherently unstable. This
theory appears to be compatible with the work of Winkley,
which was reported earlier, on maintaining a certain
channel sinuosity. Both approaches stress the importance
of working with the rivers natural conditions rather than
attempting to force the river into configurations that
suit human needs.

2. Bottom Panels. Bottom panels are reinforced
concrete slabs which are located in a manner similar to
vane dikes, (Remillieux, 51). The panels have been pri-
marily used to increase navigable depths in crossings.
Several countries have used the panels including Niger,
Chad, France, India and Thailand. A typical structure
design is shown in Figure VI-C.

Some of the advantages that the panels display
include the following:

(a) The panels are fabricated at the site
and costs are generally quite low.

(b) The panels are adaptable to a wide
variety of hydrologic conditios and may
be easily adjusted to improve their
efficiency. In fact, it is recommended

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Figure VI-C

Bottom Panel on Chao Phya River

that the panels be removed in their
early stages until an optimum efficiency
is achieved.

(c) The panels are elevated to accommodate
average low water stages and therefore
have only a negligiblie effect on flood
flows.

(d) The panels appear to be most appro-
priate, based on past experience, in
rivers with a heavy sediment load of
fine material.

3. European and USSR Experience in Revetment and
River Training. In Europe most waterways are not sub-
jected to extreme hydrological forces and, as such simpler
types of revetments are used (The following methods are
also used occasionally in the United States for reservoir
and canal bank protection).

In reaches where the ground water level is higher
than the water level in the canal, a permeable revetment
is used. Th filter layer of the permeable revetment per-
mits the flow of groundwater into the canal without
eroding the bank material. The protective layer of the
permeable revetment serves to maintain the filter layer in
place and to dissipate wave energy.

In reaches where the groundwater level is below
the water level in the canal, impermeable revetments are
used. Impermeable revetments prevent loss of water from
the canal. An example of permeable and impermeable revet-
ments are shown in Figure VI-D.

Several types of revetment with a description of
their area of application are shown in Figure VI-E. Im-
permeable revetments can be composed of an impermeable
layer of clay with graded gravel and rock protective
layers, or asphalt concrete with or without a protective
layer of rocks. Permeable filter layers can be composed
of fine gravel or synthetic material with rock or concrete
block protection.

It is emphasized that the stability of a per-
meable revetment depends mainly upon a properly structured
foundation and above all upon whether it has satisfactory

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Figure VI-D

Impermeable and Permeable Revetment Types
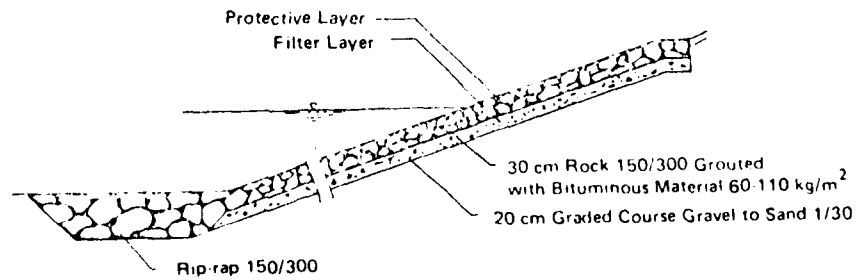
IMPERMEABLE REVETMENT
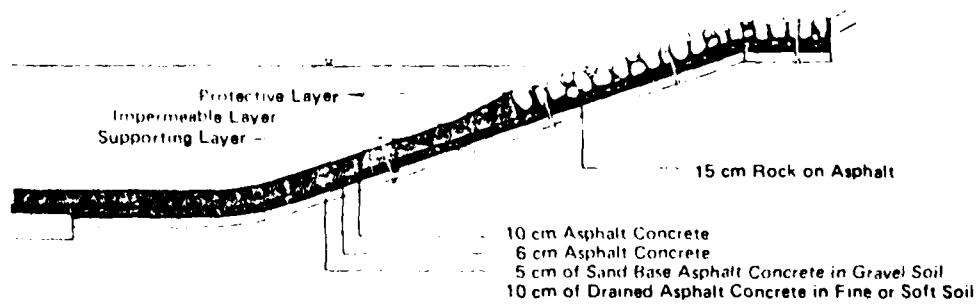
Figure VI-E

Examples of Revetments

	Type	Type of Revetment	Foundation Material	Revetment Material		Advantages for Navigation
1		Permeable revetment	Fine sand	Filter layer	20 cm of fine gravel	The smoothness of the revetment or the slopes is favorable for dumping in hydraulic jumps but unfavorable in terms of resistance to vessel movement
				Revetment	30 cm of rock of grain size 150/250 maintained in place with bituminous material 80-110 kg/m²	
2		Permeable revetment	Marl alluvium with fine sand	Filter layer	Woven material with a coefficient of permeability between 0.01 and 0.1 cm/sec	Concrete block revetment is smoother than rip-rap and offers less resistance to vessel movement
				Revetment	Concrete blocks 14 × 14 × 69 cm. Revetment of the upper slope: Terrain system	
3		Impermeable revetment	Sand and gravel	Impermeable layer	30 cm of clay	Same as 1
				Protective layer	20 cm of gravel and coarse gravel. Bottom: 50 cm of coarse gravel	
				Revetment	40 cm of rock, grain size 250/350	
4		Impermeable revetment	Fine sand	Impermeable layer	30 cm of 100/150 surface	The revetment/bottom and bank is relatively smooth and is favorable in terms of resistance to vessel movement
				Protective layer	rip-rap held together with colloidal cement	
				Revetment		
5		Impermeable revetment	Sand	Impermeable layer	6 cm of bituminous concrete on 3 cm of bituminous sand	Little energy loss on the smooth revetment and therefore favorable for navigation
				Revetment	10 cm of bituminous concrete for the underwater section	
6		Sheet pile wall with permeable or impermeable bottom	Any type of soil	No special protection required for the vertical walls		Particularly favorable for navigation because of the favorable profile and smoothness of the bottom

filter stability, especially in the area of the slope exposed to waves and water level fluctuations. Particular attention must therefore be given to the filter arrangement.

Compared with the United States approach to revetment and bank stabilization projects less area below the water level is covered by the revetment material under the European approach. It has been found that while capital expenditures are lower in Europe the life expectancy of the structures are shorter and the maintenance and repair expenditures are many times higher.

River Training in the Union of Soviet Socialist Republics is based on standard evaluations of hydrology, channel morphology, and navigation needs. Three dimensional physical modeling in movable beds is employed in complex cases. Several interesting design features have been described by Russian authors.

The constriction width (W_c) of a channel reach is determined by the following equation:

$$W_c = \left(\frac{h_s}{0.85h}\right)^{3/2} W_s$$

where
W_c = constriction width channel
h = desired depth of navigation
h_s = controlling depth of crossing
W_s = width of navigation channel

Channel alignment, in terms of least radius channel curvature permitted, is determined by the relation of constriction width (W_c) multiplied by a factor of 4.5 or 5.0.

In order to determine the length (L) of a dike the following relation is used:

$$L = \frac{W - W_c}{\sin \psi}$$

where
L = length of dike
W = channel width
W_c = constriction width
ψ = angle formed by the dike and current

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Other studies suggest that spacing of dikes should be a distance of three to four times the dike length and that sloping crest dikes are preferrable when the dike is designed to be submerged. Both of these relations are similar to the Corps experience in the United States.

ONGOING RESEARCH

Researchers at the Waterways Experiment Station are currently undertaking research relating to river training in the area of dike design, channel alignment, revetment, and bank stabilization and math modeling.

Under the WES Dike Research Program, phase I efforts are in progress to optimize dike design criteria in river crossing sections. Four specific variables are being modeled. These are dike height, angle, profile or slope, and spacing. A phase II effort will evaluate the same variables in a river bend section. It is expected that this research will be completed in 1983. Since a hydrograph characteristic of the lower Mississippi River will be simulated in the model studies, it is questionable as to whether the research will have complete applicability outside of the LMVD unless other hydrographs are tested.

Research into the principles of channel alignment has been proposed. This has been prompted by the morphological effects that cutoffs and other river training structures have had on the Lower Mississippi River. It is hypothesized that sinuosity is a key element in maintaining stable channels. The research is presently in a literature review stage which will formulate the hypothesis regarding channel alignment. A second and third phase will be to conduct model studies and to verify prototype results respectively. The program is expected to continue over four years.

The revetment and bank stabilization research has been described earlier. A major goal of the Section 32 program is to identify cost effective conditions of revetment applications. It is generally believed that the quality of construction and maintenance are the key elements in effective bank stabilization. The program is expected to produce an engineering manual for bank control structures and a set of pamphlets emphasizing regional self help guidelines.

Low cost materials for self help project by local land owners also is considered a promising field of investigation. This investigation has only marginal applicability for major navigation channels but may produce local benefits to secondary channels. Waste products such as rubber tires are being tested. Such products are currently being discussed and field tested. A list of possible techniques provided by Oswalt et. al. (t0) is given below:

1. Used rubber tires, as a mattress laid on the bank, lashed together with metal bands, held down with screw anchors, and filled with native soil or gravel.

2. Tires, as a bulkhead staggered vertically toward the bank, filled with sand and gravel, and capped with concrete-filled tires.

3. Tires, stacked vertically completely enclosed inside a double-row wire and pole fence with stone toe protection, parallel to bank with tiebacks at regular intervals.

4. Tires, stacked vertically on staggered pole fence with top board, parallel to bank with tiebacks at regular intervals.

5. Tires, for floating breakwater, lashed together with conveyor-belt edging and nylon bolts, with supplemental floating provided by foam fill to prevent the breakwater from sinking when the sediment load is high, anchored with rectangular-shape concrete blocks.

6. Soil cement blocks formed by stabilizing locally available sand, cut into various size blocks, and placed on the bank as an artificial rip rap.

7. Hay-filled wire crib retard, with stone protection, parallel to bank with tiebacks at regular intervals.

8. Membrane encapsulated soil system placed on bank with stone toe protection.

9. Aluminum grid sections pressed into bank with induced vegetation.

10. Use of locally-available materials such as furnace slag, concrete rubble, and low-quality rock for revetment.

The Waterways Experiment Station is currently attempting to identify the effects of navigation on bank protection requirements using rip rap as the base test in comparison to prototype at a 1:20 scale. While navigation produced waves and bottom erosion from propeller wash are minor compared to other causes of streambank erosion it may be locally significant. Criticism of navigation effects are significant in some areas and therefore research appears justified to document solutions to site specific erosion problems.

Other areas of navigation related research have included assessment of zones of no wake or limited speed zones in areas susceptible to erosion. Offbank mooring buoys near lock entrances will increase the distance between ships and banks thus reducing erosion according to preliminary studies in the ORD.

Field measurements and the analytical assessment of the impacts that tow traffic has on river bed stability are underway in the Huntington District. This study is a part of the Gallipolis Lock and Dam study being conducted jointly by Louis Berger and Associates, the Huntington District and WES.

VII - DREDGING TECHNOLOGY

A great deal of research has been performed in the past few years and is ongoing in the field of dredging.

The bulk of the work has been directed towards developing methods to reduce the impact of dredging operations on the environment. This includes efforts to define the nature of the impacts of dredging and disposal techniques, wherever deemed necessary. Most of the studies have been very site specific, primarily because the nature of the requirements are generally very site specific recommendations for the continued maintenance of the Upper Mississippi River involving potential modifications of dredging volumes and dredging techniques. These studies have primarily centered around the Corps hydraulic cutterhead dredge Thompson.

To a great extent, the technological developments discussed in some of the subsequent sections have come partly as a result of individual studies and partly through attempts by the Corps of Engineers and private industry to develop a technology which may be appropriate to meet present and future requirements and considerations. It is likely, at least in the short term future, that these requirements will continue to be defined on a site specific basis or require that site specific studies be conducted to define the requirements. However, it is appropriate to mention two studies whose objectives were to develop criteria for dredging and dredge material disposal on a general or national level.

The Dredged Material Research Program [51] (DMRP) which was undertaken by the Waterways Experiment Station of the Army Corps of Engineers is now essentially complete. It consists of more than 250 individual studies which were intended to form a technological basis for use in all subsequent aspects of dredging project design and implementation. "The DMRP was designed to be as broadly applicable as possible on a national basis with no major type of dredging activity or region or environmental setting excluded."

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To those concerned with national or regional planning and policy formulation, there are two extremely important fundamental conclusions that can be drawn from DMRP. The first is that there is no single disposal alternative that presumptively is suitable for a region or a group of projects. Correspondingly, there is no single disposal alternative that presumptively results in impacts of such nature that it can be categorically dismissed from consideration. Put in different terms, there is no inherent effect or characteristic of an alternative that rules it out of consideration from a technical standpoint prior to specific on-site evaluation. This holds true for open-water disposal, confined upland disposal, habitat development, or any other alternative.

The second basic conclusion is that environmental considerations are acting more strongly than possibly any force to necessitate long-range regional planning as a lasting, effective solution to disposal problems. "No longer can disposal alternatives be planned independently for each dredging operation for multiple projects in a given area. While each project may require a different specific solution, the interrelationships must be evaluated from a holistic perspective and thought given to when particular disposal alternatives may have to be replaced with others as conditions change. Regional disposal management plans not only offer greater opportunities for environmental protection, ultimately at reduced project cost, but also meet with greater public acceptance once they are agreed upon." (From "Final Summary - The Dredged Material Research Program," Vol. D-79-2, June 1979.[52])

A research project entitled "Improvement of Operation and Maintenance Techniques" (IOMT) is now underway at the Waterways Experiment Station of the Army Corps of Engineers. Currently, three work units are being pursued.

In the work unit entitled "Effect of Depth and Width on Dredging Frequency," a literature survey of methods now being used to predict the effect of deepened conditions in a dredged navigation channel on shoaling were investigated; an evaluation of the effectiveness of advance maintenance was performed. Reports classifying navigation

projects according to behavior and developing rational criteria for use in evaluating advance maintenance is currently being prepared.

The second work unit, "Advance Maintenance for Entrance Channels," is just getting underway and scheduled for completion in 1983. It is to be used to develop rational criteria for the use of advance maintenance for entrance channels and the effect of depth and width on dredging frequency and volumes.

The third work unit, "Advance Maintenance for Riverine Channels," is still in the proposal stage.

Several new concepts are undergoing development to improve dredging plant design. Development efforts are not concentrated in general programs but conducted by private companies and government agencies. Research in the development of dredging equipment is addressed in the sub-section entitled "Trends in Dredging Plant."

HISTORICAL
GENERAL DREDGING
PRACTICE

Historically, the general dredging practice employed in connection with the maintenance of the nation's waterways was to utilize that type or combination of dredge plant, transport system and disposal method which would accomplish the dredging objective effectively, at the lowest overall cost. The major consideration associated with the dredging activity and its evaluation was on the basis of economics. However, other factors including environmental, were given consideration, but generally only when there was definitive data and knowledge that a particular dredging or disposal technique would have a detrimental effect on the waterway or adversely affect other concerns or interests. As examples, no open water disposal operations were performed at, and in, the vicinity of active oyster or shellfish beds, or near any water intake structures.
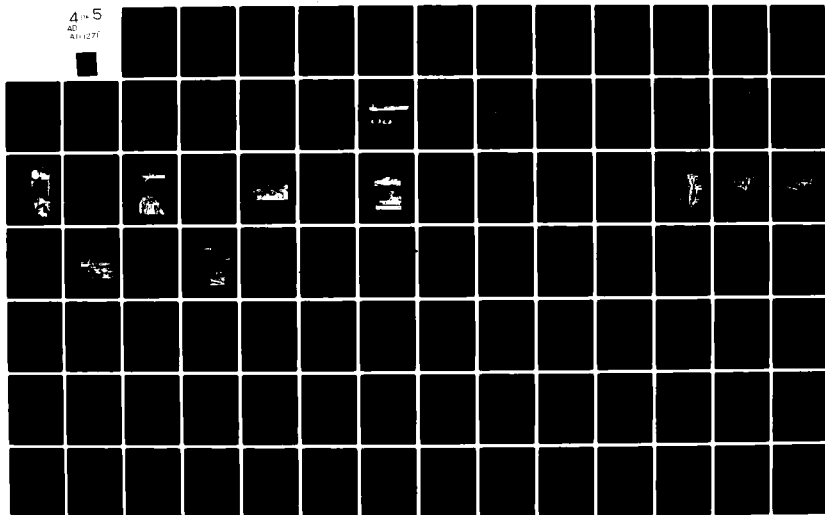
Thus, in the past, the general practice was to consider open water disposal adjacent to the dredging area, generally the least costly method, as a first choice, unless such method of disposal would result in undue or rapid shoaling or reshoaling of the project channels or the waterways at nearby facilities or if known detrimental effects dictate otherwise. If in the application of this overall general practice, it was found that open water disposal was not practical nor desirable, then the next choice was disposal in upland areas either confined by dikes or embankments (provided areas suitable for the purpose and advantageously located from an operational cost standpoint were available).

Beyond these disposal methods, the options were very limited. If the project was near an ocean inlet or a relatively large body of water, i.e., Great Lakes, open water disposal in the ocean or lake areas was a viable option. However, if none of the dredging and disposal options indicated heretofore were practical and could not be utilized, then the only alternative was to accept any adverse shoaling in the adjacent channels resulting from open water disposal, the first choice option, and to consider the dredging operation for the project less cost effective than expected.

The historical general dredging practice resulted in the majority of the dredging work, especially in the inland waterways, being accomplished by cutterhead hydraulic pipeline dredge and dustpan dredge. In the deeper draft coastal harbors, the predominant dredge type was the trailing suction sea-going hopper dredge. Mechanical dredges such as the clamshell and dipper dredges were also utilized in both inland and coastal projects, but only to a minor extent.

It can be seen that the past general dredging practice was influenced greatly by economic considerations. However, since the mid 1960's there occurred an increasing awareness in the United States to the extent that other requirements and considerations also played an important, and oftentimes more significant, role than economic consideration in the evaluation of the feasibility of the dredging project and/or acceptability of the proposed dredging plant and operation. These considerations were

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not limited to a particular facet of the dredging activity but in many cases were applied to all phases thereof, that is, the dredging process itself, the transport of the dredged material and the method and place of disposal. In addition to the emergence of the need for consideration of factors other than economic as well as economic factors in the evaluation of dredging activities, it was found, through research studies and demonstration projects, that in many instances the dredged material itself can become a valuable resource and, as such, could generate significant benefits. Thus, the productive use of the dredged material is also an important factor to consider when evaluating a dredging activity and the dredging techniques to be selected for its accomplishments.

DREDGING PRACTICE
OPTIONS

Under current practices and those in the foreseeable future, environmental and other requirements, productive use opportunities and cost effectiveness will be the critical factor controlling the direction of a dredging activity. Consideration of these factors will impact on the need for modifications in operational techniques, dredging plant technology and disposal methods and practices. In many instances, significant changes have already been affected. It is most likely that the trend to improve dredge technology will continue so that compatibility is established between all facets of the dredging operation and the ecological values which must be preserved as well as to extract maximum benefits from the productive use of the dredged material.

It should be emphasized that while, historically, general types of dredges have evolved which have been able to work effectively over a range of physical conditions, specific requirements and considerations often transcend physical boundaries so that a dredge which is cost effective under one overall setting may be much less cost effective under another setting.

(a) Alternative
Setting

At this point a general overview will be presented on the effect on dredging methods and technology of different

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settings based on specific dredging or disposal require-
ments and considerations.

Five possible settings can be hypothesized (dredging
and disposal requirements varying from mild to severe) for
which different dredging and disposal options are indi-
cated. These are illustrated below.

For a determination of the appropriate dredging
techniques at a particular location, the settings must be
determined on a site specific basis and the conditions
peculiar to the specific site recognized and given the
required consideration.

The first setting is the ideal case where the dredging
and disposal requirement is favorable in that general open
water discharge of the dredged material adjacent to the
dredging area or along the banks of the waterway is the
acceptable practice. In this instance, assuming open
water disposal is not objectionable from a shoaling stand-
point, the normal dredging technique is to employ a cutter-
head hydraulic pipeline dredge or dustpan dredge, depend-
ing on the waterway, with direct pumping to the open water
area or within the bank disposal areas. However, to
obtain maximum operational efficiency, the dredge should
be of the optimum size commensurate with the depth of the
average cutting bank on the job (see discussion National
Waterways Report, "Analysis of Waterways System Capa-
bility"). As a general rule, when the cutting bank is
small, a smaller size dredge will be more efficient, and
vice versa. In coastal and lake areas, the use of a
hopper dredge is an alternative.

The second hypothetical setting assumes that because
of the contaminated nature of the bottom material to be
dredged and the extent of the ecological values at and in
the vicinity of the dredging site which must be preserved,
the disposal considerations require that the material be
placed in upland areas either confined or unconfined as
appropriate. Further, that suitable disposal areas are
available in the general vicinity of the dredging site.
Under the conditions of this setting, the most appropriate
dredging plant and method of disposal would be to
accomplish work with a cutterhead hydraulic pipeline

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dredge with direct pumping to the upland area, maximizing
operational efficiency by selecting the proper dredge
based on the cutting bank criteria. However, depending on
the distance to the disposal area and the lift required,
some compromise may be required in the size selection in
order to assure that horsepower requirements are satisfied.

A third hypothetical setting assumes the same general
requirements as in the second setting, but in addition, no
upland disposal area sites are available in the nearby
vicinity. However, there is a disposal alternative a few
miles distant from the dredging site where the disposal
requirements and considerations provide for open water dis-
posal at that location. It is obvious that the material
would have to be transported to the open water site. If
the disposal site is located within two booster stations
(three in some special cases) from the dredging area, the
use of a cutterhead hydraulic pipeline dredge would be one
alternative. (Note: While theoretically there is no
limit to the number of boosters that may be used in a
pumping operation, in dredging operations for navigation
purposes, the use of two or three boosters is generally
the practical limit because of operational problems
associated with the more frequent mechanical breakdowns,
shutdowns due to operational requirements and synchroni-
zation of the booster stations with the dredging plant.)
A second alternative is the loading of scows at the
dredging site, transporting the material in the scows to
the open water dump site and dumping the material there-
in. This alternative suggests two methods by which the
material could be dredged and the scows loaded. A
clamshell dredge could be used to load the scows (this is
the more common method), or a cutterhead hydraulic pipe-
line dredge could be utilized to pump dredging techniques
- filling the scow to the maximum effective load by
filling beyond overflow and allowing the reentry of some
fraction of the dredged material into the waterway or
loading only to overflow to preclude the spilling of any
dredged material into the waterway but not obtaining the
maximum effective load. The choice depends on the
dredging requirements and considerations applicable in the
area. If the bottom material in the dredging area is of
such nature, its re-suspension and eventual deposition in
the waterway would have an adverse effect such as blocking
of a back channel or slough, then the dredging consider-
ation would probably require that the scows be loaded by
pumping only to overflow. It should be pointed out that

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because of the greater rate of filling and more intense
agitation of the material in the scow associated with the
hydraulic scow fillng operation than with a clamshell
dredge operation, generally there is also less settled
material in the scow when overflow is reached. Another
alternative or option in this scenario might be to use a
type of plant similar to the Corps special purpose dredge,
Currituck. This plant is a small, shallow draft, split-
hull type, self-propelled, trailing suction hopper dredge
presently used in relatively shallow ocean bar inlet
channels. However, there might be a possibility that this
type plant could be adapted to the requirements of the
inland waterways.

A fourth hypothetical setting assumes a relatively
severe condition, that the disposal requirements and con-
siderations are such that disposal can only be affected by
upland disposal in confined areas adjacent to the water-
way, but such suitable areas are located several miles,
more than two or three booster stations, from the dredging
site. One obvious dredging technique alternative is to
load scows or barges with either a clamshell or hydraulic
dredge, transport the material to a convenient unloading
site near the available upland disposal area, unload the
material mechanically into trucks and transport it to the
disposal site. An unloading alternative is to unload the
material hydraulically by means of a rehandling system or
barge unloading plant which fluidizes the material in the
scow or barge and pumps the slurry to the upland disposal
site. Another alternative method, if appropriate for the
site conditions, is to use a hopper dredge with direct
pumpout at the disposal site to the disposal area.

A fifth hypothetical setting assumes that the same
general requirements and conditions similar to those of
the previous setting (setting four), but in addition there
exist significant numbers of previously used upland diked
disposal areas adjacent to and along the waterway. These
areas have been used in the past and are filled to capac-
ity. Under this scenario, there are two additional
dredging technique alternatives. The first might be to
restore the capacities in several of these disposal areas
by re-excavating the material and transporting it inland
to more distant locations where it is assumed disposal
sites would be more readily available. The material
transport could be accomplished hydraulically with special

equipment or the material removed mechanically and trucked. These techniques are addressed in W.E.S. Technical Report D-78-28[53], one of the studies accomplished by the Waterways Experiment Station under the DMRP. The second alternative might be the application of techniques which have as their objective means of increasing the capacity of disposal areas in that it might make available some remaining capacity in disposal areas ideally located for receiving material directly from the dredging sites. Certain types of dredged material deposited in disposal areas by the hydraulic process contains vast amounts of water which remains trapped for extended periods of time beneath a hard crusty surface. This prevents evaporation and drying of the moisture laden material entrapped beneath the surface layer and valuable capacity in the disposal area consequently is wasted. Techniques and equipment have been developed by the Waterways Experiment Station under the DMRP where the material is significantly dewatered and densified, thereby increasing the effective capacity of the disposal areas. (See W.E.S. technical reports TRD-78-27 and TRDY78-12, Dredged Material Research Program).

Table VII-1 depicts the five hypothetical settings presented above by their salient features.

Although the settings discussed above were hypothesized, actual experience during the past decade shows a trend in which the disposal requirements and related considerations for many dredging projects have resulted in greater transport distances to the place of disposal be it in open water or in upland areas. This trend suggests that the transport phase of the overall dredging operation will bear a greater portion of the cost of the operation because of the more distant disposal areas. It also suggests that dredging methods and techniques will change and adapt to the extent required so as to assure continued maximum cost effectiveness. It appears that because of the greater transport distance, increased application might be made of different types of mechanical dredges, such as the bucket ladder, clamshell, dipper, mounted backhoe or dragline, etc., with the transport mode being of the tug/barge/scow combination. However, hydraulic dredges will most likely continue to perform the preponderance of the national dredging

Table VII - 1

Dredging Technology
(for 5 hypothetical settings)

Setting No.	(Dredging & Disposal Requirements)	Dredge Used	Land Transport Transport Mode	Upload Method	Disposal Site	Remarks
1	Open water disposal at dredging site	Dustpan or Cutterhead Hydraulic	Pipeline	Discharge directly into open water	Open Water	Ideal case. In coastal areas the use of hopper dredges is prevalent with disposal in ocean
	upland areas in general vicinity of dredging sites	Cutterhead Hydraulic with booster	Pipeline	Discharge into upland disposal area	Upland Area	
3 Alt. 1	Open water disposal within two booster stations distance of dredge site	Cutterhead Hydraulic with booster	Pipeline	Discharge directly into open water	Open Water	Not practical where more than 2 or 3 booster stations are required
Alt. 2	Ditto	Cutterhead or Mechanical	Scow/barge	Dump	Open Water	
Alt. 3	Ditto	Small Hopper Dredge	H.D.	Dump	Open Water	Small shallow draft split hull trailing suction similar to Corps Currituck
4 Alt. 1	upland areas located long distance from dredging site	Cutterhead or Mechanical	Scow/Barge	Mechanical and Truck	Upland Area	In coastal and Great Lakes projects hopper dredges are also used with direct pumpout to upland areas
Alt. 2	Ditto	Ditto	Ditto	Hydraulic rehandling pumping equipment	Via pipeline to upland disposal area	
5 Alt. 1	In existing upland areas along waterway but capacity requiring the restoration of disposal area capacity	Special excavating plant to remove material from existing disposal area	Pipeline	Discharge into distant upland area	Distant Upland Area	Technique to reestablish capacity in existing nearby disposal areas. See DMRP Report D-78-28
Alt. 2	Ditto	same as above but using mechanical equipment	Truck	Ditto	Ditto	Ditto
Alt. 3	Ditto	Dewatering or densification equipment	N/A	N/A	N/A	Technique to increase capacity of existing areas by dewatering and densification

workload. In addition, the greater transport distances
might make the small trailing suction hopper dredge an
economical alternative in many selected cases. One could
expect that this trend will generate a greater effort in
the field of research and dredge technology. However, to
place the above views in proper perspective, one must have
knowledge of the big picture that is, what is the status
of the dredge fleet. Is it adequate in numbers, type and
condition, to provide for the present and future needs of
this country's waterways. This was addressed in detail in
the report "Analysis of Waterways System Capability," and
the reader is referred to that report. However, some
general observations, comments and conclusions based on
and derived from the data in the above mentioned report
can be made with respect to the current and future federal
dredging activities and operations by both private, and
government owned dredging plant. These observations focus
on the basic question as to whether the present dredge
plant in the country, both privately owned and government
owned, can in a timely and efficient manner, adequately
maintain the nation's inland waterways. The observations
stem from an analysis of the data in the National Dredging
Study and the principles in connection with the establish-
ment of a minimum government dredge fleet as required by
PL 95-269. Briefly, they are as follows:

    The present capacity of the existing federal and
private dredging plant is generally geographically distrib-
uted on a basis which is approximately in proportion to
the work requirements in the several regions. Although
there could be an occasional deficiency in plant of a
specific type, it would in all probability be confined to
a particular region and be of short duration and of minor
consequence. There is a degree of mobility in the
dredging industry, especially between adjacent regions and
the industry has often demonstrated that it can respond
positively to crisis situations. In addition, the
government plant is available to assist in overcoming any
shortfall in contractor plant. With respect to the
establishment of the governments by the dredging industry
in the Corps dredging program and probably increase
industry's share of the federal dredging workload from
60-65% currently to above 75%. As industry's dredges are
currently under utilized there is sufficient reserve
capacity available for the additional workload.

The present dredging fleet, both private and government is generally old and some of it obsolete. However, despite its condition, the existing dredge plant is generally adequate and federal project waterways. The condition of the dredging plant is probably reflected in somewhat higher costs of dredging; but as plant is improved and modernized, dredging costs should stabilize. It is expected that with the greater utilization of plant by industry and the highly competitive nature of the dredging market, that a more positive plant modernization and replacement program will develop to meet the challenge of the requirements of new dredging techniques and procedures to confirm with current and future needs. Industry has recently acquired a new modern dustpan dredge, the first one to be owned by other than the Federal Government as well as several trailing suction hopper dredges. Other dredges, both of similar and different types, are in the planning stages. This indicates that a positive industry program of plant replacemnt, modernization and addition is now in progress. Besides, the plant in the government's minimum dredge fleet will be of the most modern type and should include features necessary to provide for any special future needs.

Dredging requirements on many of the inland waterways depend primarily on hydrological conditions, thus there may be marked seasonal and annual variations in these requirements. Naturally, the question is raised whether existing dredge plant is sufficiently flexiblie to meet these fluctuating requirements. As previously indicated, the dredging plant has a certain degree of mobility. Of paramount importance to a dredging company is to effect maximum utilization of the plant. Thus, in areas of fluctuating requirements, movement of plant to and from adjacent regions, depending on requirements, gives the degree of flexibility required to meet seasonal and annual variations in demand. This, of course, could be augmented by plant in the government's minimum dredge fleet, which by direction, will have a high degree of mobility and flexibility.

Dredging techniques and procedures, in the future, will be governed to a large extent by the specific requirements existing or imposed at the time, and technology is generally available, or could be developed, to adequately handle the requirements in an effective manner.

Technology to meet disposal considerations has been developed and documented in reports in connection with the Corps recent Dredged Material Research Program. In addition, within the private dredging industry, there is a vast reservoir of technical expertise. This suggests that research and development activities should be a joint effort between government and industry and that there should be a high degree of coordination and cooperation to assure that dredging technology will be available in the event future needs so dictate.

In addition to the above observations, the following conclusions from the Report "Analysis of Waterways System Capability" in which trends are discussed with respect to quantities of material to be dredged, the techniques to be used in dredging and disposal of dredged material and the operational requirements for dredging equipment are included below since it focuses on the several major issues and concerns:

The following trends are discernible:

1. Efforts to minimize quantities of dredged material for a maximum level of service to shipping will be emphasized.

2. Dredging methods and methods of disposal of dredged material will be determined on a site specific basis.

3. Transport distances from dredging site to final point of disposal of dredged material will probably increase.

4. Increasing emphasis will be placed on 'beneficial' or 'productive' uses of dredged material.

These trends have the following implications for dredging needs:

1. Improving procedures for determining dredging needs.

2. Increasing control of dredging and improving positioning technology to minimize differences between

gross (actual volume dredged) and credited (material within designated dredging prism) volumes dredged.

3. Modifications and improvements to dredges and support equipment to improve their ability to handle different methods of disposal, such as upland, beach nourishment, marshland creation, scow loading and for productive uses, etc.

4. Increased density of slurry to reduce overall dredging costs and possibly to reduce environmntal problems.

5. Development of more efficient methods for transport of dredged material greater distances.

(b) Productive Use
     of Dredge
     Material

An important facet of any dredging operation is the possibility that benefits might be derived from productive use of the dredged material and in connection therewith, create viable disposal opportunities. Oftentimes, these disposal opportunities emerge in areas where disposal alternatives were practically nonexistent. In some instances, benefits accruing to localities from productive use concepts for the dredged material have become an element of tradeoff in developing disposal alternatives for the project. It is expected that these considerations will become of greater importance in the future. A brief discussion of some of the more important productive use concepts follows:

The beneficial uses of dredge material are numerous (many of which have become recognized through the work of the DMRP. One of the obvious and extensively employed beneficial uses is in land filling or in construction. Dewatered material that has been found free of contamination has been used, donated, and sold in some cases. Normally, the material is utilized at or near the containment site for such purposes as haul road construction or dike raising by Corps districts. The use of dredge material for expanding industrial zones during port construction projects has been found to be particularly valuable.

The creation or improvement of wildlife habitats has been a significant use of dredge material in nearly all parts of the country. However, it is recognized that most past occurrences were primarily accidental rather than planned. It was realized that even the most productive habitats can be out of place within an ecosystem and consequently the DMRP concentrated on understanding the natural processes encountered at disposal sites. As a result, guidelines have been developed which consider all aspects of dredge placement from site selection for follow-up management.

Wildlife habitats have been developed both in marsh and upaland ecosystems. Marsh creation has been field tested and proven as a viable alternative. While marsh creation is not a simple or inexpensive operation when compared with many other alternatives, it is an operation that can be planned in such a way so as to accommodate maintenance dredging for long periods into the future. The engineering considerations are not particularly difficult, but dredge operators may be required to perform operations that will require coordination.

The development of upland habitats is a technology that is more advanced and more tested than marsh habitat development. Upland habitat include food, cover, and nesting for mammals and waterfowl. Most of these require only the application of existing agronomic and wildlife management practices. Dredge material is being employed to create specific land topographies, and in combination with selected plantings of vegetation, are designed to accommodate ecological niches for specific animals or groups of animals. Most varieties of upland game are included, but wildlife sanctuaries for animals requiring particular attention has also been accommodated.

Small islands created by dredge material along the inland waterways and coastal bays are a special type of upland habitat development. More than 2000 of these islands have been created and have beomce extremely valuable wildlife habitats for such birds as seagulls, terns, and herons.

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A further part of the DMRP was the development and testing of concepts for non-wildlife oriented beneficial or productive uses of either dredged material itself or disposal sites. Successful use of dredge material or dredge sites are described as requiring, in most instances, favorable and fortuitious circumstances. It appears that non-technical factors outweigh technical factors in the potential develoment process and that a high degree of coordination and cooperation in land use planning is required. Some of the uses of dredge material in this category which are believed to have commercial potential include the obvious uses; aggregate and brick for the building industry. However, this use has not developed to any appreciable degree, nor is any increase in the future anticipated. More exotic uses include the mariculture of shrimp where the disposal site forms the required impoundment and the organic rich dredge material is a periodically renewed source of food for the shrimp. This technology is only in the experimental stage, but if the efforts prove successful, it could become a significant use for dredge material.

If dredge material can be economically moved over distances of tens of miles, there are real opportunities for the improvement of agriculture soils, use of coarse grained dredged material in solid waste management, the filling of abandoned pits and quarries, and strip mine reclamation.

Within the domain of recreational land use, clean sand has been profitably utilized in beach creation and beach nourishment. This has been proven to be especially useful in areas where erosion is actively reducing beach areas or in the creation of beaches on inland waterways. The Upper Mississippi River is an area, for example, with an abundance of clean sand which has been proposed for creating small recreational areas for pleasure craft awaiting passage through locks an dams.

While the beneficial uses of dredge material have been found to have much potential above their role in the part, there are areas in which research is still being aimed to further gain knowledge in this area. There are three major areas of investigation being conducted by WES and other research institutions. These are the study of

vegetation succession on fill sites, the study of uptake of pollutants by plant materials, and the monitoring of lechates from disposal sites.

Studies have shown that the productivity of minor species in some cases is greater than anticipated and that some species have the ability to recover from being buried beneath dredge material up to several inches thick. Many dredge sites are expected to be revegetated by artificial means and the nature and quality of the succession is being evaluated.

It appears that most of the beneficial uses described in this section will not present any insurmountable obstacles to the dredging process. Although some slight modifications to the customary dredging practices and dredge plant technology may be necessary, no difficulties or complex probem areas are apparent. Habitat development, bank stabilization land fill and beach creation projects would generally be accomplished by hydraulic dredge by techniques similar to the first setting, and the alternatives one and two of setting three as described earlier. For strip mine reclamation, fill for abandoned pits and quarries and other productive use concepts which require dredged material at sites remote from the dredging area, the second and fourth settings would be applicable. The dreding methods indicated above for productive use concepts are the basic dredging techniques only. In addition, there will probably be requirements for certain refinements and additions such as processing activities, dewatering, classifyin, densificaton and separation. Technology for these activities are available and only requires the application of the techniques, on a site specific basis, to the dredging process. Guidelines have been developed on how the Corps and other groups can achieve or promote the productive use of dredge sites and material and it is expected that the future will allow increased opportunities of these beneficial uses.

(c)   Effect on Cost
       of Degree of
       Severity of
       Disposal
       Requirements

In general, it can be stated that as the requirements
and considerations for disposal increase in rigidity and
severity, the overall costs of a dredging operation in-
crease accordingly. It is apparent (referring to hypo-
thetical settings four and five in Table VII-I) that the
options for the dredging techniques to be adopted for
these settings may be extremely costly. In some in-
stances, a re-evaluation of project. Oftentimes, although
technological improvements or advances in dredging equip-
ment will improve operating efficiency to the extent that
overall dredging costs may be less than before, usually
such improvements are overbalanced by increased costs re-
sulting from changes required in dredging methods because
of the more rigid disposal requirements and considera-
tions. It appears that as greater emphasis is placed on
these requirements and more rigid disposal criteria and
controls are established, that despite technological im-
provements and new innovations in dredging equipment and
practices, there still will be some upward acceleration of
dredging costs exclusive of the effects of inflation
factors.

Improvements in dredge technology and in efficiency of
dredge operation are basically the two main elements which
tend to counteract to some degree the increased dredging
costs resulting from the more rigid disposal requirements.
To place this subject in proper perspective, a review of
the status of research in dredge technology, various de-
velopments in dredges and their application and recent im-
provements and trends in operational techniques and dredge
construction is needed.

(d)   Trends in
       Dredging Plant-
       Application and
       Improvements

There exists no industry-wide research program
directed towards the development of new dredge types and
their application or improvements in dredging systems,

equipment and components. Generally, such applied research and development efforts have been and continue to be undertaken on an individual basis by the Corps of Engineers, certain manufacturers of dredges and dredging equipment and a few dredging contractors, both in the United States and abroad. Over the years, these efforts have led to many significant dredging plant improvements, modifications and operational innovations, including certain recent developments as discussed herein. Looking towards the future, there is an apparent need for integrating and coordinating these efforts with the view towards effecting a purposeful program of dredging equipment development and improvement with due consideration of present and anticipated needs and constraints. A combined effort of this nature would serve to ensure effective and economical solutions to difficult problems that may be encountered in the construction and maintenance of present and future waterway projects. Also in the light of the continuing energy crisis, it is imperative that all possible means of improving the energy-effectiveness of dredging plant by reducing fuel consumption by installing modern power plant equipment and adopting waste heat recovery measures must be given increasing consideration.

A Dredging Research Institute has been established in Japan which is understood to be government sponsored with industry contributions. In The Netherlands, the Delft Hydraulic Laboratory conducts research in dredge technology under the sponsorship of the governement and private industry; and in addition, Delft University has a curriculum for educating and training dredging engineers. In the Union of Soviet Socialist Republics, several specialized research laboratories conduct continuous programs in the area of dredge plant development. A Center for Dredging Studies established at Texas A & M University in the United States has similar objectives but has not yet been developed to its full potential.

A description of the most common dredging plant types and their normal use is included in the Report "Analysis of Waterways System Capability" of the National Waterways Study. As indicated therein, dredges are generally of two types - mechanical and hydraulic with three principal variations of the latter, namely the hopper dredge, the cutterhead dredge and the dustpan dredge, handling the bulk of dredging work on federal navigation projects. It

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was also noted in the above mentioned report that the pre-
ponderance of existing dredges (both federal and private)
in these categories are old and obsolescent compared to
similar plant of modern design. Although this dredge
fleet may be considered adequately capable of performing
the foreseeable dredging workload, modernization unques-
tionably is desirable in order to increase overall effec-
tiveness to accomplish work under varying conditions
dictated and/or influenced significantly be present and
anticipated disposal practices and related considerations.

Basically, recent technological advances and
developments in modern hydraulic dredge design relate
mainly to provisions for increased power, deeper dredging
capacity, centralized controls, and monitoring the
dredging process. Power requirements generally are being
well served by applications of medium speed diesel
engines. The application of submerged dredge pumps is
resulting in increased dredging depth capabilities as well
as heavier concentrations of solid/water mixtures.
Centralizing controls on the bridge and lever room serve
to decrease operator's response time and thus enhance
production and safety. Monitoring of the dredging process
involves the use of instrumentation to sense and display
principal dredging parameters and thus provide guidance in
controlling the operation of dredging machinery and
equipment at optimum or desired efficiency levels. Such
instrumentation supplemented with logic circuits and
processing equipment (e.g., electronic computers and
micro-processors) required to evaluate input data and make
logical choices now provide means for semi-automating or
automating the dredging process.

Various improvement features developed during recent
years that have been or are being incorporated in modern
hydraulic dredges (domestic anid foreign) of the three
principal types used for maintaining waterways are briefly
described below. These innovations generally are intended
to improve productivity and overall efffectiveness,
including the increase of versatility or range of dredge
applications. It should be noted that certain of the
features described have been known for a decade or more
while others are under current development and need to be
tested and evaluated in connection with further develop-
mental efforts.

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1. <u>Hopper Dredges</u>. The various improvement
features relevant to hopper dredges are as follows:

(a) Provisions for self-unloading hoppers by
     direct pump-out through pipelines ashore
     into confined disposal areas or on
     beaches for nourishment purposes.

(b) Installation of bow thrusters for
     increased maneuverability at slow speeds
     and during docking and undocking,
     particularly when engaged in direct
     pump-out operations.

(c) Installation of doppler ground speed
     indicators that provide accurate and
     continuous measurements of ship speeds
     and thus assist the operator in
     maintaining trailing operations that
     result in optimum pumping of diverse
     bottom materials.

(d) Split hull type construction that
     permits rapid bottom dumping of dredged
     material and the use of shallower
     disposal areas. See Figure VII-A.
     Great Lakes Dredge and Dock Company
     presently owns and operates two dredges
     of this type in the United States and
     has a third under construction. Also,
     three others are under construction for
     C.F. Bean Corporation and T.L. James.
     Relatively small shallow draft plant of
     this type, such as the Special Purpose
     Dredge Currituck owned and operated by
     the Corps of Engineers, can be used as a
     sand by-passing plant disposing of
     dredged materials directly into the surf
     zone of beaches on the downdrift side of
     coastal inlets.

(e) Installation of dragarm-mounted
     submerged dredge pumps for increased
     dredging depth capability beyond 60-70
     feet as well as increased density of
     pumping mixtures.

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Figure VII-A

Split-Hull Type Trailing Suction Hopper Dredge
(Courtesy of IHC Holland)
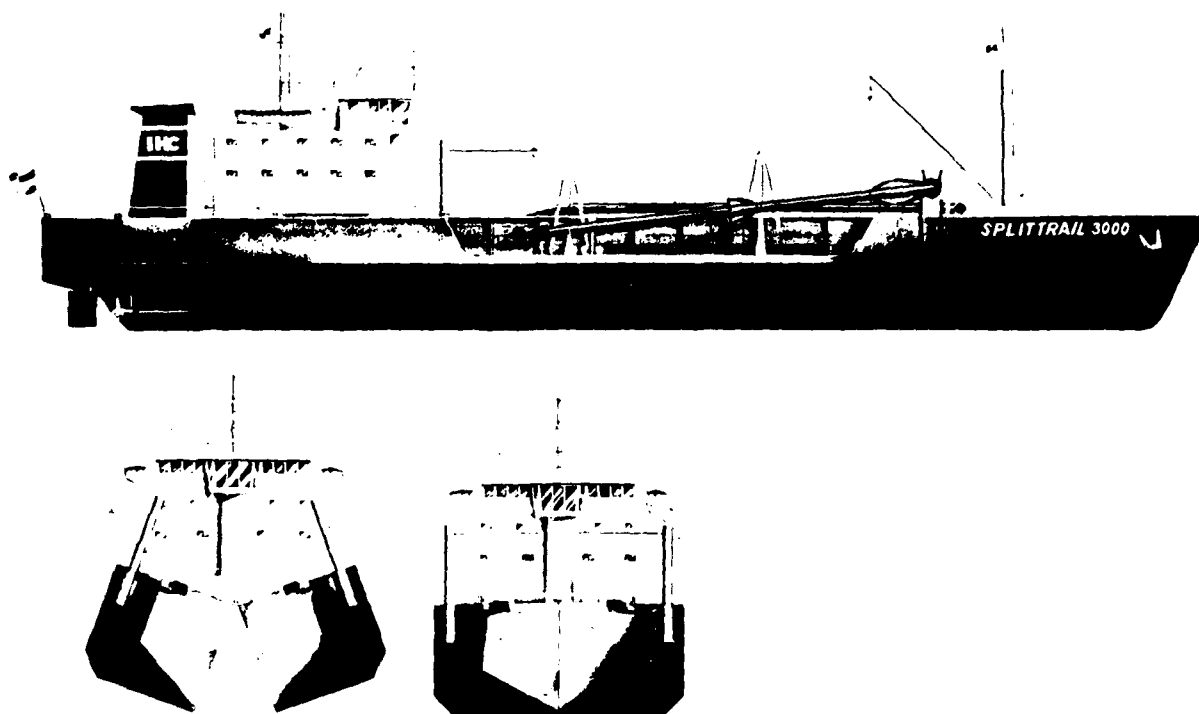
(f)   Use of improved dragheads, such as those
      equipped with digging teeth and or high
      pressure water jetting apparatus for
      dredging compacted sand (see Figure
      VII-B), and the so-called "Active
      Draghead" (developed by IHC Holland) for
      dredging hard cohesive bottom materials
      (e.g., stiff clays), which permit
      trailing suction hopper dredges to
      dredge difficult-to-dig bottom materials
      more effectively and thus enhance the
      versatility of this type of dredge.

(g)   Centralizing dragarm handling and dredge
      pump controls at a single operating
      station to permit one-man operation of
      multiple dragarm/pump installations thus
      effecting a reduction in crew
      requirements.

(h)   Installation of variable overflows that
      permit the hopper overflow level to be
      continuously adjustable and thus
      optimize loading operations under
      limited draft conditions and regardless
      of burnout conditions.

(i)   Installation of "anti-turbidity"
      overflow systems, such as that developed
      by the Japanese firm of dredge builders,
      Ishikawajima-Harima Heavy Industries
      Company, Ltd. (IHI) (see Figure VII-C),
      to reduce surface (visible) turbidity in
      surrounding waters when loading hoppers
      by pumping beyond overflow.

(j)   Use of corrugated rubber hose type
      flexible joints, in lieu of ball and
      socket joints, in dragarm suction
      assemblages to reduce the adverse
      effects from possible leakage.

(k)   Variations of hopper distribution sys-
      tems and related controls designed to
      reduce turbulence in the hoppers, obtain
      better solids retention (reduced over-
      flow losses) and provide for improved

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Figure VII-B

Draq Heads (Courtesy Ishikawajima, Harima Heavy
Industries, LTD.)

Self adjustable drag head

Drag head with digging teeth
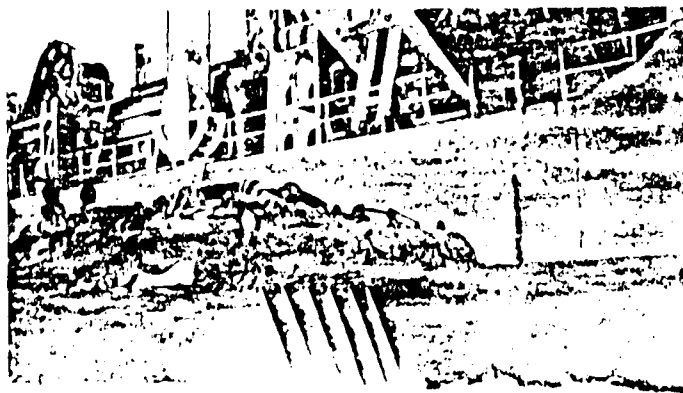
Demonstration of drag head jetting

Figure VII-C

(Courtesy Ishikawasima Harima Heavy Industries, LTD.)

Conventional overflow system

Anti-turbidity overflow system

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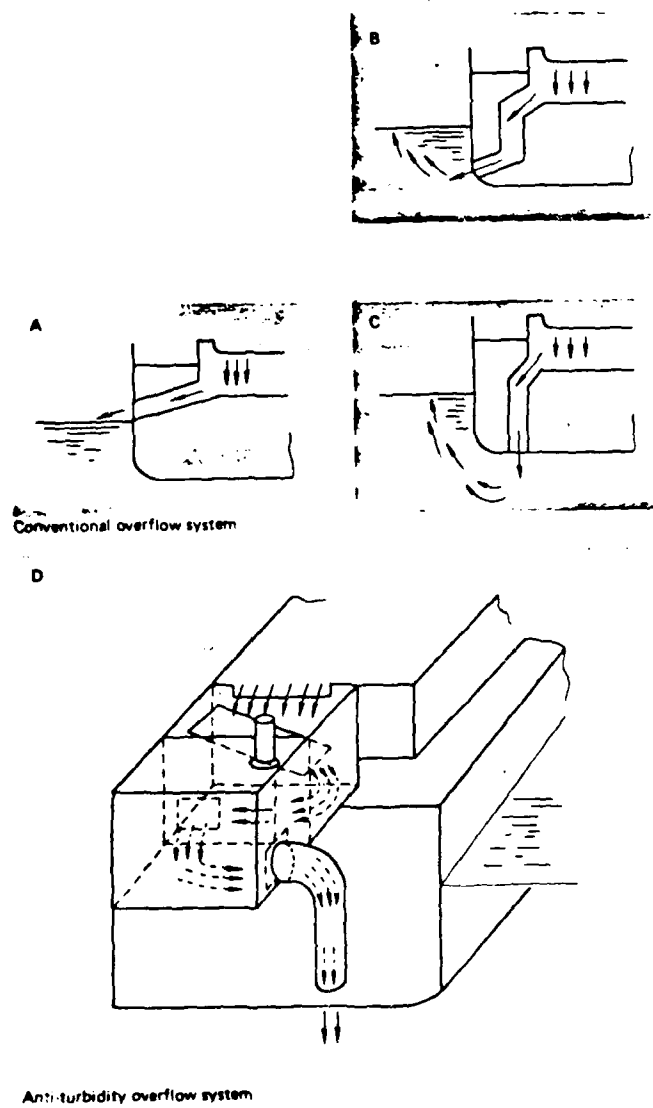
longitudinal vessel trim control with
resultant improvements in overall hopper
loading efficiency.

(l) Use of horizontal sliding type hopper
     dump doors for dredges designed for
     dumping in very shallow water, such as
     close to a shore or beach. This type
     door installation is significantly more
     costly than other conventional types and
     therefore is provided only when dictated
     by special operational considerations.

(m) Provisions for automating portions or
     all of the dredging process. Generally,
     new hopper dredges of modern design are
     being provided with means for automatic-
     ally controlling the lowering, hoisting
     and stowage of suction dragarms. In
     conjunction therewith, means are pro-
     vided for continuously indicating the
     orientation of the entire dragarm and
     the position of the draghead in a
     profile and plan display. On two of the
     three hopper dredges currently under
     construction for the Corps of Engineers,
     essentially the entire hopper dredging
     process is being automated, including
     provisions made for operating with
     constant draft loading as may be deemed
     advisable under certain job conditions.

(n) Installation of Automatic Light Mixture
     Overboard (ALMO) control systems that
     provide for automatically discharging
     overboard (rather than into the hoppers)
     dredged mixtures lighter in density than
     pre-set levels. This feature is partic-
     ularly advantageous when dredging light
     materials comprised of fine-grained
     silts that are relatively non-retainable
     and hopper loading is accomplished by
     pumping to overflow only. It will be
     noted, however, that there could be
     environmental objections to the use of
     such systems in certain areas. This

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system also could be adapted for use in Agitation Dredging where feasible and permitted.

(o) Installation of the maximum number and size of hopper doors that are permitted by structural design in order to facilitate bottom dumping operations.

(p) Provisions for enhancing the capabilities of hopper dredges for use in emergency situations such as firefighting and oil spill recovery. For example, IHC Holland has developed the design of a combination trailing suction hopper dredge/oil recovery vessel which is currently under construction for a consortium of dredging contractors in The Netherlands. (See Figure VII-D.)

2. Cutterhead Dredges. The various improvement features relevant to cutterhead dredges are as follows:

(a) Use of cutterheads of advanced design that are specifically suited for the particular type bottom material in order to increase production. For example, cutterheads with rock cutting teeth have been developed which are significantly more effective than previous versions.

(b) Installation of improved anchoring systems including so called "christmas tree" arrangements to permit dredging in coastal waters exposed to wave action that precludes operation with conventional spuds.

(c) Substitution of cutterhead with other suction-type wheel excavating devices such as the so-called "Bucket Wheel" developed by Ellicott Machine Corp., and the "Dredging Wheel" developed by IHC Holland. (See Figures VII-E and VII-F.)

Figure VII-D

Trailing Suction Hopper Dredger/Oil Recovery Vessel (Courtesy IHC Holland

310
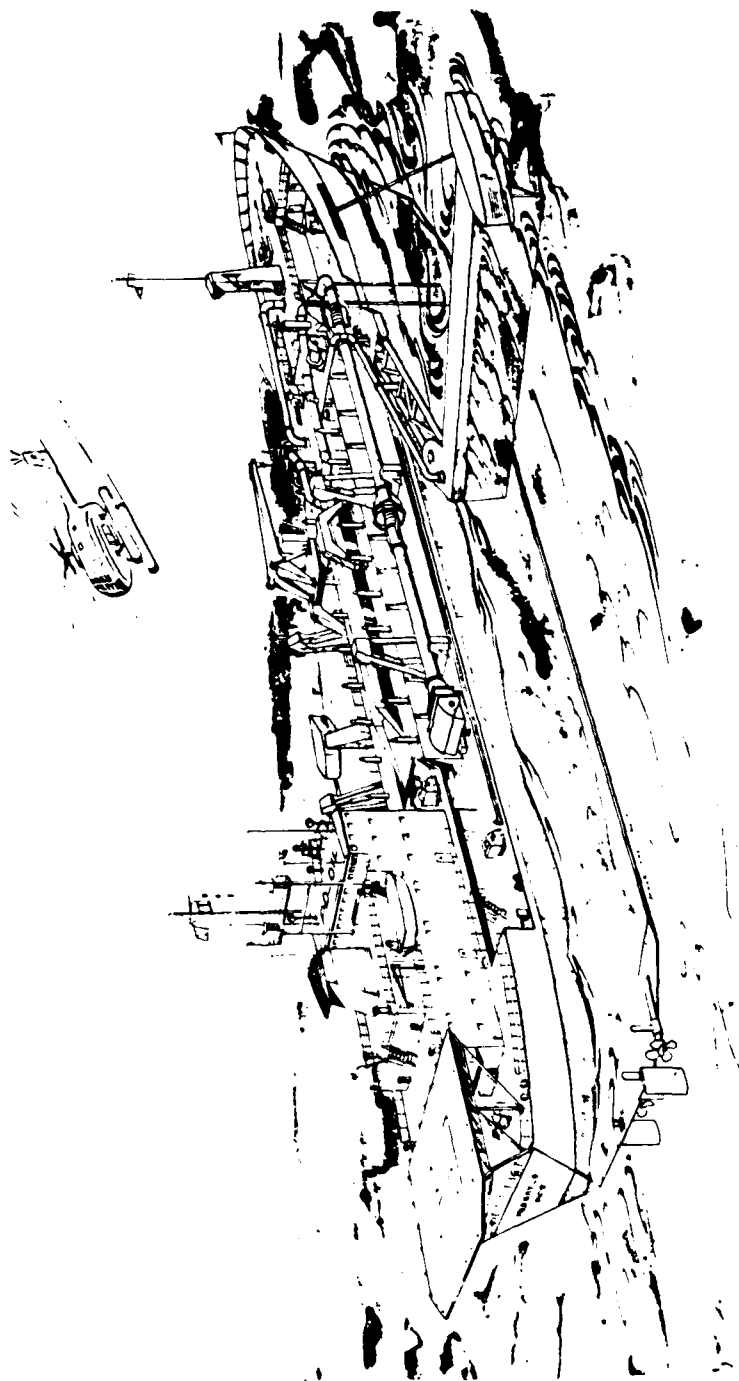
Figure VII-E

Underwater Bucket Wheel Excavator (Courtesy of Ellicott Machine Corp)
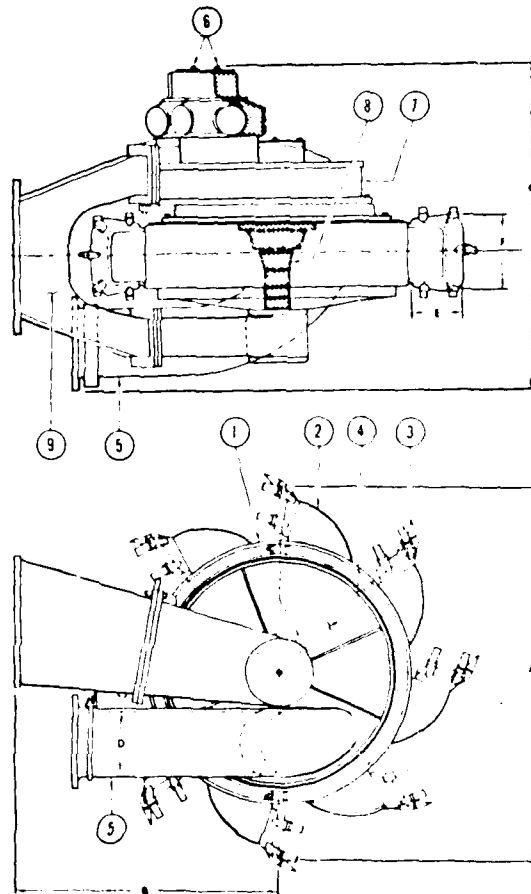
Figure VII-F

IHC Dredging Wheel

(Courtesy IHC Holland)

312
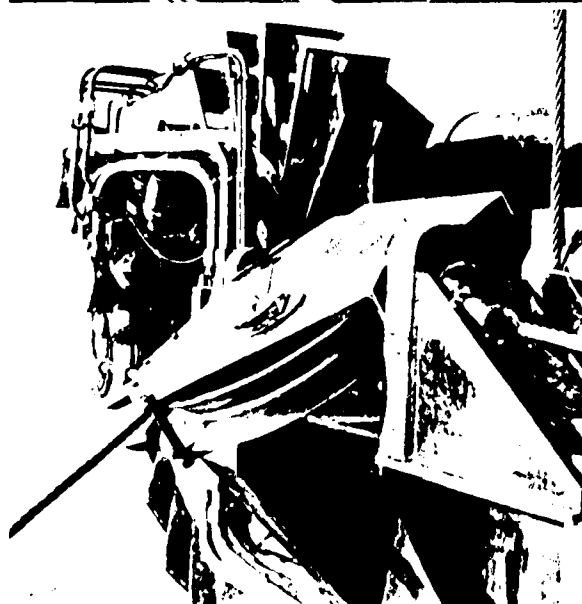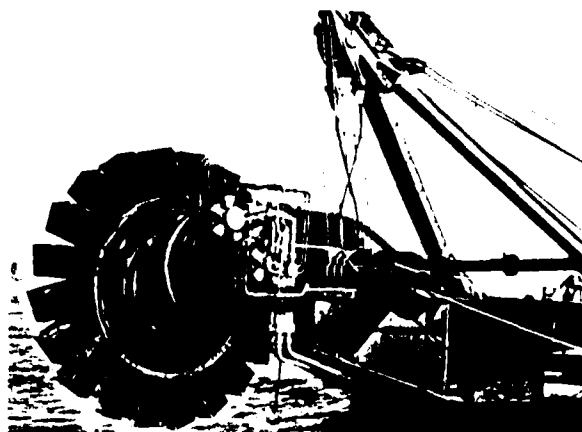
(d)   Installation of dredging process instru-
        mentation and automatic cutter control
        equipment in order to effect automatic
        control of the dredge operation (i.e.,
        swing speed, solids concentration,
        etc.,) in a manner that produces maximum
        output under prevailing conditions.

(e)   Provisions for self-propulsion for
        improved mobility thereby facilitating
        shifting operations required from
        shipping traffic, adverse weather and
        sea conditions, etc. This feature
        serves to improve the limited working
        capability of cutterhead dredges in
        coastal waters exposed to sea waves as
        well as permitting more rapid mobili-
        zation and demobilization for trans-
        ferring between dredging assignments.
        (See Figure VII-G.) (Note: Two Corps
        of Engineers' cutterhead dredges, namely
        the W.A. THompson and the Ste. Genevieve
        used in inland waterways are self-
        propelled.)

(f)   Installation of ladder-mounted submerged
        dredge pumps for increased dredging
        depth capability as well as increased
        density of pumping mixtures.

(g)   Installation of a second inboard dredge
        pump which when operated in series with
        the main pump permits pumping through
        longer pipelines without booster
        stations. New self-propelled cutterhead
        dredges recently constructed in the
        Netherlands are equipped with two in-
        board dredge pumps as well as a
        submerged dredge pump. This arrange-
        ment permits the dredge to deliver
        dredged material into hopper barges
        moored alongside and through long dis-
        charge pipelines to disposal areas as
        much as five miles from the dredging
        area. (See Figure VII-G.)

(h)   Installation of swell compensating
        devices on the ladder support rigging in

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Figure VII-G

Self-Propelled Cutter Suction Dredge

(Courtesy IHC Holland)
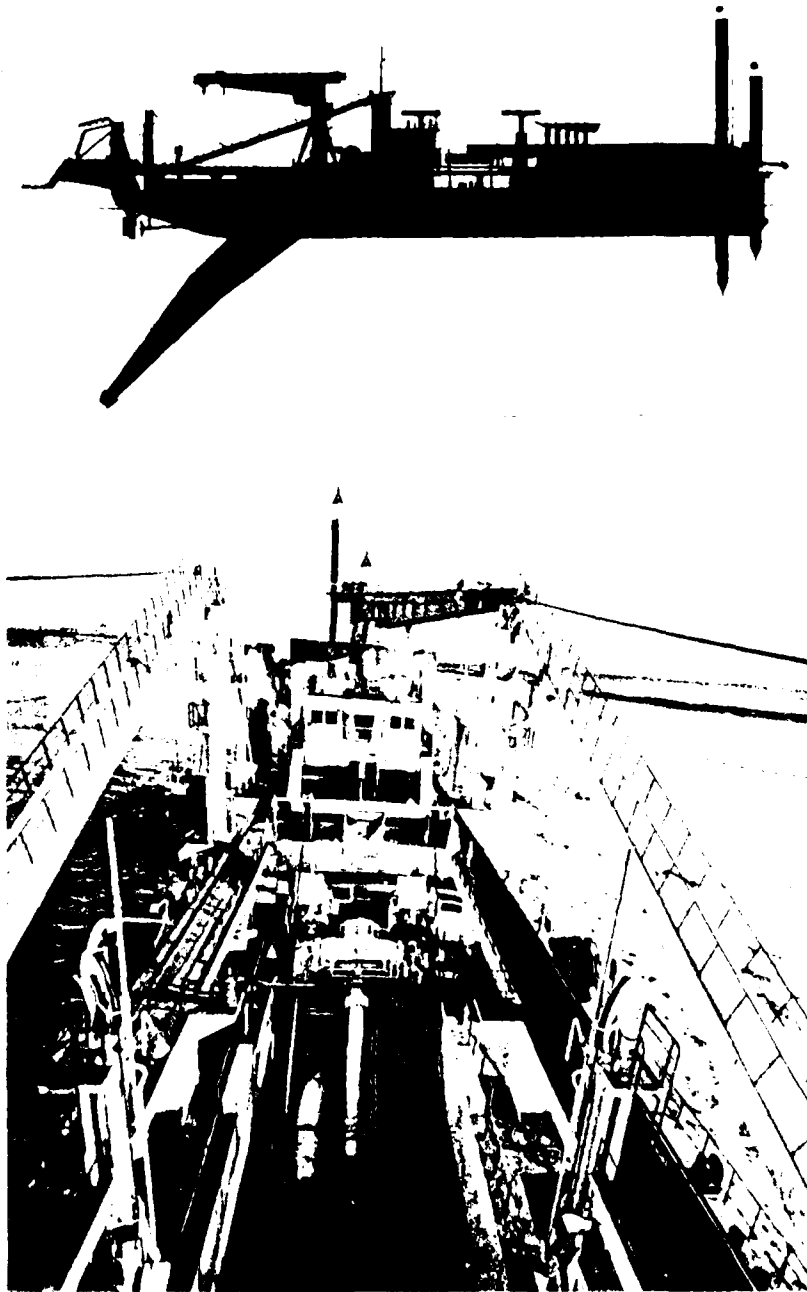
order to permit more effective cutter
action under swell conditions.

(i)   Installation of improved shafting seals
        (in lieu of conventional stuffing boxes)
        on high pressure dredge pumps such as
        those used in series operation when
        pumping through long pipelines. (Note:
        IHC Holland has developed a mechanical
        sealing arrangement which is used on its
        standard, double-walled dredge pump (see
        Figure VII-H) designed for high pressure
        service).

(j)   Improved means of loading hopper barges
        with dredged material that consequently
        would be unloaded by bottom dumping or
        with barge unloading plant.

        Although this is not in the category of new tech-
nology or new innovation, the required use of electric
dredges under certain circumstances is worthy of mention.
Pursuant to air and noise pollution requirements, it is
reported that a local jurisdiction required dredging to be
performed with electric dredges rather than with dredging
plant using fossil fuels. Since there are limited numbers
of electric dredges in the country, any extension of such
requirements could impact on dredge fleet availability.
It should be noted that electric dredges have limited use
because they depend upon the availability of adequate
electric power and facilities in the vicinity of the
work. It is felt that a restrictive requirement of this
nature is unreasonable and ill advised.

        3. Dustpan Dredges. As previously indicated in
the report on "Analysis of Waterways System Capability,"
the Corps of Engineers dustpan dredge fleet consists of
five steam-powered units all of which were built in 1932
or 1934. Consequently, these dredges must be considered
obsolete except possibly for fundamental elements of the
dredging system, such as the dredge pumps, the suction
head, etc., which presumably have been modified and up-
dated in design over the years, particularly to reflect
operating experience over nearly 50 years. Unques-
tionably, any new dustpan dredge design will incorporate
modern power plant machinery and equipment that will be

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Figure VII-H

Double-Walled Dredge Pump (Courtesy IHC Holland)
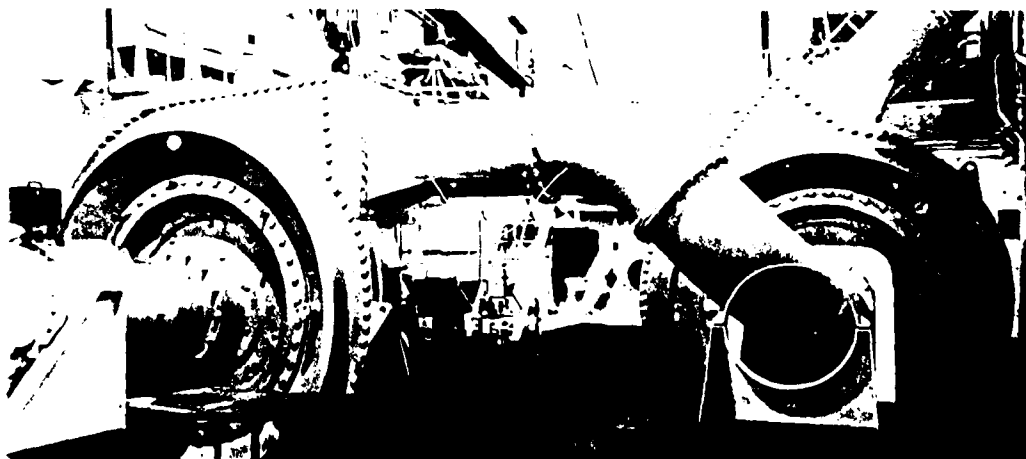
significantly more efficient than those on these existing dredges. In addition, a number of the improvement features, such as those related to automation or semi-automation of the dredging process similar to those indicated for the other hydraulic dredges above, certainly would be equally applicable to the dustpan dredge.

Last year (1979) a new privately owned dustpan dredge was placed into operation. (See Figure VII-I). This dredge, the LENEL BEAN, is owned and operated by the C.F. Bean Corporation of New Orleans, Louisiana. This dredge originally was a booster unit whose hull subsequently was expanded to become a cutterhead dredge and then was re-designed in 1977 into a 38 inch diameter (discharge) dustpan dredge. The LENEL BEAN is a diesel-powered with propulsion through two Z-drive units that provide 360-degree steerability of propellers and high maneuverability without conventional rudders. The dredge pump and jet pump are both driven by a single 3600 hp diesel engine with a double output gear box. The ladder and anchor hoists and auxiliary pumps are DC electric-motor driven with power taken from an AC diesel-generator set through silicon controlled rectifiers for converting the AC output to DC. All equipment is of the latest design for marine service. During the present year, the dredge has been operating under Corps of Engineers contract for main-tenance dredging on various crossings of the Mississippi River above New Orleans. While no performance report of its operation has been published to date, it is understood that its operation has been satisfactory although, as in new plant, an initial "debugging" period was experienced.

4. Mechanical Dredges. Mechanical dredges of the clamshell bucket and dipper types probably will continue to be used to some extent in the future (if not to the same degree as at present). Consequently, consid-eration must be given to technological developments in this type of dredging plant. For example, clamshell buckets with improved digging capabilities as well as equipment designed with closures to reduce turbidity have been developed that could have potential applications in waterway dredging. Also, automation of certain elements of the mechanical dredging process conceivably could be adopted. Instrumentation that displays the digging angle of dipper and backhoe type dredges has already been developed in Europe.

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Figure VII-I

Dustpan Dredge Lenel Bean

(Courtesy C.F. Bean Corporation)
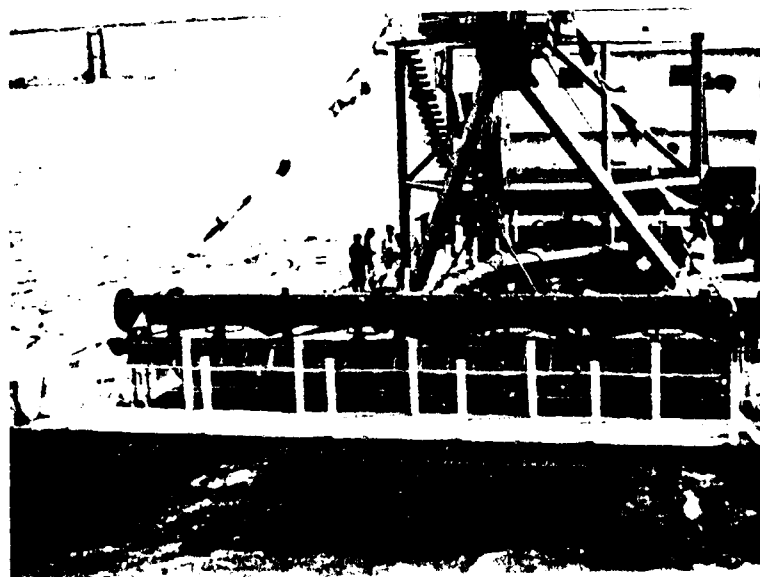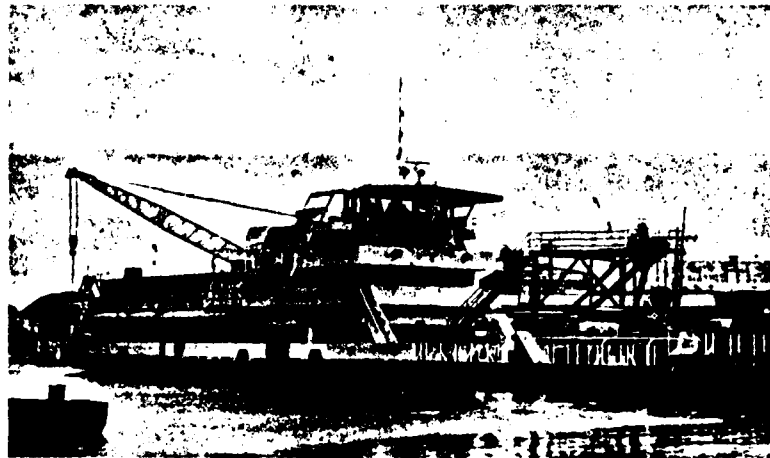
5. __Other Dredge Types.__ Although it is generally anticipated that hydraulic dredges of the type indicated above will continue to be employed for most dredging work required to maintain waterways in the United States in the future, cognizance must be had of the development of the other types of dredging equipment that is currently in progress. A representative number of developmental type dredging plants or systems (domestic and foreign) that could be applied or adapted for navigation channel dredging, particularly when special circumstances exist, are described briefly below.

(a) PNEUMA PUMP: This is a pneumatic type dredging unit developed originally in Italy that utilizes compressed air to pick up and pump bottom materials. It has beeen claimed that this pump can handle solids/water slurries at higher densities than those obtainable by conventional hydraulic dredges. However, limited testing of a unit recently conducted in the Wilmington District of the Corps of Engineers did not verify such claims and indicates that a pneuma-type pump might have application for dredging highly contaminated sediments as well as for deep dredging when very limited volumes are involved. (See Figure VII-J.)

(b) OOZER DREDGE: This is a specialized dredging system developed in Japan for clean-up dredging of highily contaminated sediment. It utilizes a modified pneuma-type pump which is equipped with a scooping device to pick up the sediment and feed it into the pump, and a vacuum-assist to help force the material through the pump. Demonstration testing of the oozer dredge in Japan has been observed by Corps of Engineer personnel and other United States representatives and there appears to be significant interest in possible applications in certain waterways (e.g., James River, Virginia) where highly contaminated sediments exist. (See Figure VII-K.)

Figure VII-J

Operating Principle of the Pneumatic Pump

(Courtesy of Pneuma North America, Inc.)

FILLING PHASE   DISCHARGE PHASE

WATER SURFACE

COMPRESSED AIR   DISCHARGE

INLET VALVE

INLET

BOTTOM SEDIMENT
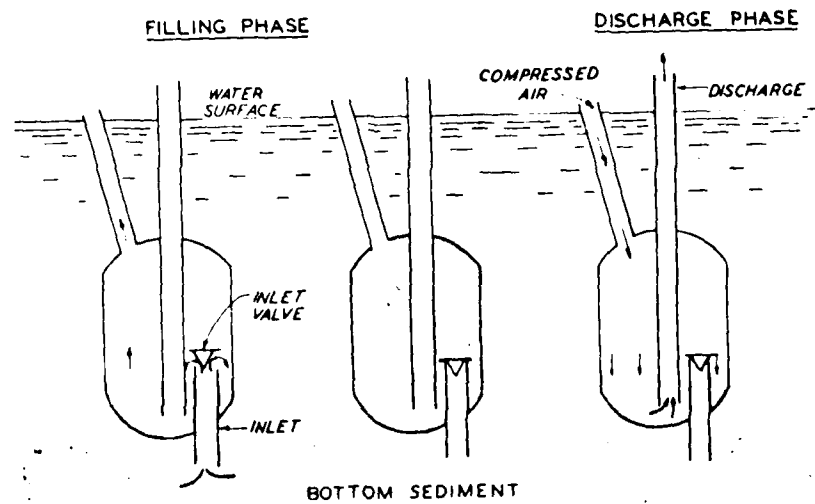
Figure VII-K

Oozer Dredge "Clean Up No. 5"

(Illustration Courtesy TOA Harbor Works Co., Ltd.)
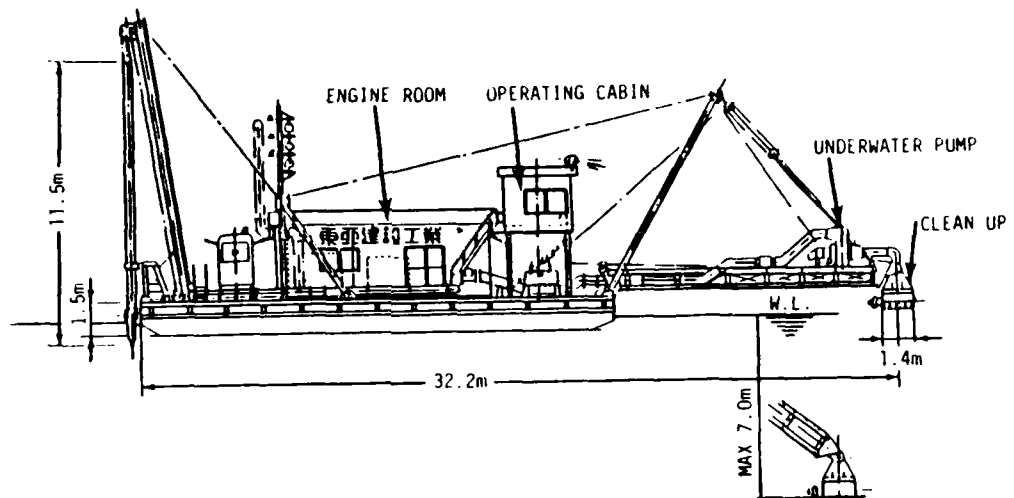
(c) SELF ELEVATING AND SEMI-SUBMERSIBLE TYPE DREDGES: Various developmental type hydraulic dredges mounted on semi-submersible module and/or supported on self-elevating platforms have been designed primarily to overcome obstacles to dredging hard material in heavy swells. A very large capacity dredge of this type is understood to be under construction in The Netherlands for the Royal Volker Stevin Dredging Group, for various uses in rough coastal waters, including pipeline trenching, mining, entrance channel deepending and the construction of artificial offshore islands. (See Figure VII-L). Also, IHC Holland recently announced development of two new dredge designs, namely the SSD (Semi-Submersible Dredge) and the WADSEP (Walking and Dredging Self-Elevating Platform) of this general type, in response to the apparently increasing attention being given to the problem of performing cutter suction dredging in ocean swell conditions. Obviously, such plant could have future application for constructing and maintaining coastal port channels in the United States (See Figures (VII-M and VII-N.)

(d) AMPHIBIOUS EQUIPMENT: Over the past ten years or so, several amphibious earth movers and excavating machines were introduced in Japan. One was basically a standard bulldozer modified into a watertight vehicle and adapted for working under water. Another is a hydraulic type automatic digging machine. Both of these units are un-manned and guided by radio. In addition, IHC Holland in The Netherlands has developed and is marketing a series of small amphibian dredging units that are readily transportable for operation in remote areas. These machines consist of a pontoon with three or four hydraul-ically-operated movable legs that permit

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Figure VII-L

Semi-Submersible Walking Cutter Platform (Courtesy Royal Volker Stevin)
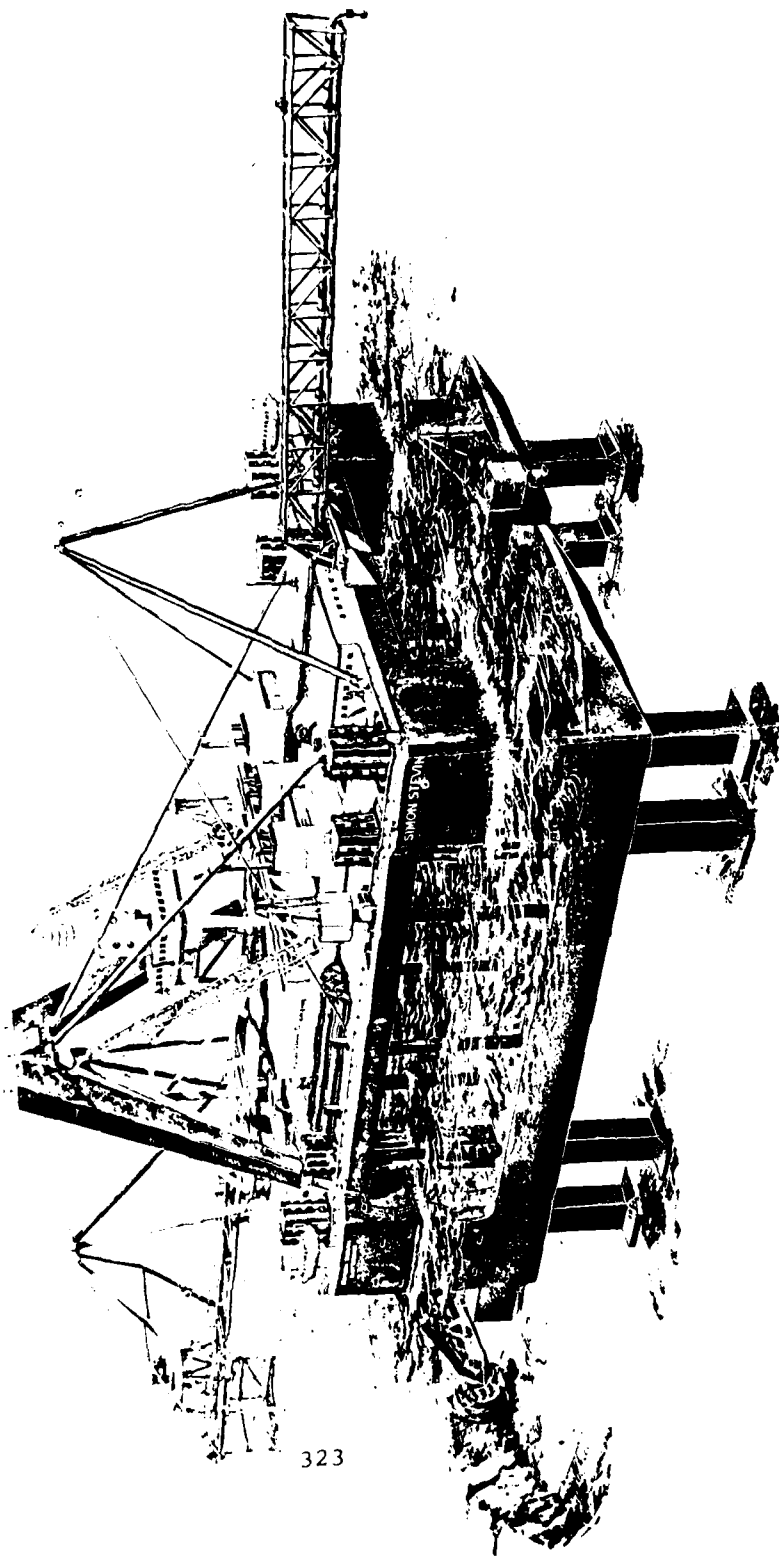
Figure VII-M

Semi-Submersible Dredge (Courtesy IHC Holland)
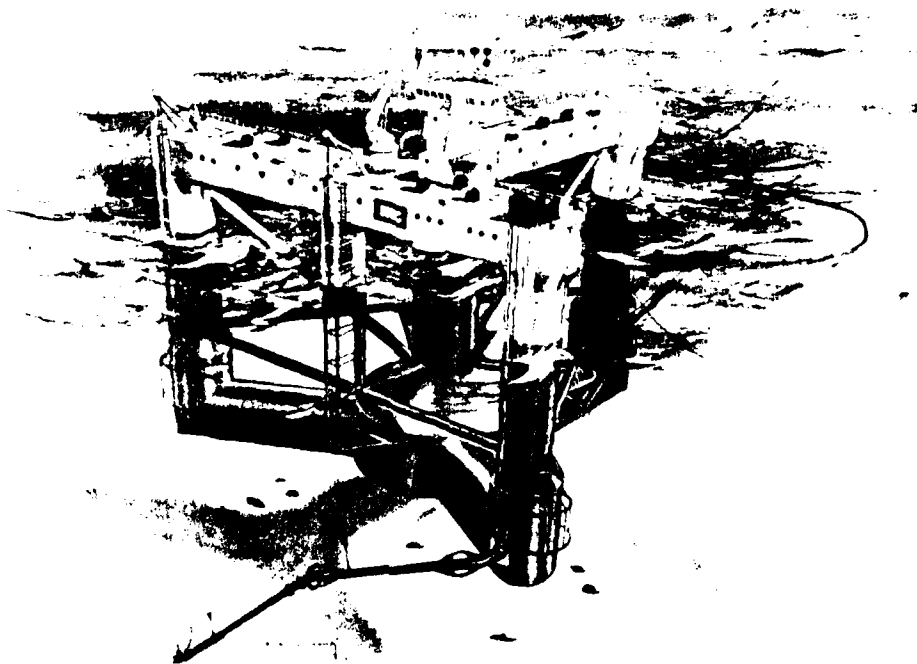
Figure VII-N

Walking & Dredging Self-Elevating Platform

(Courtesy IHC Holland)
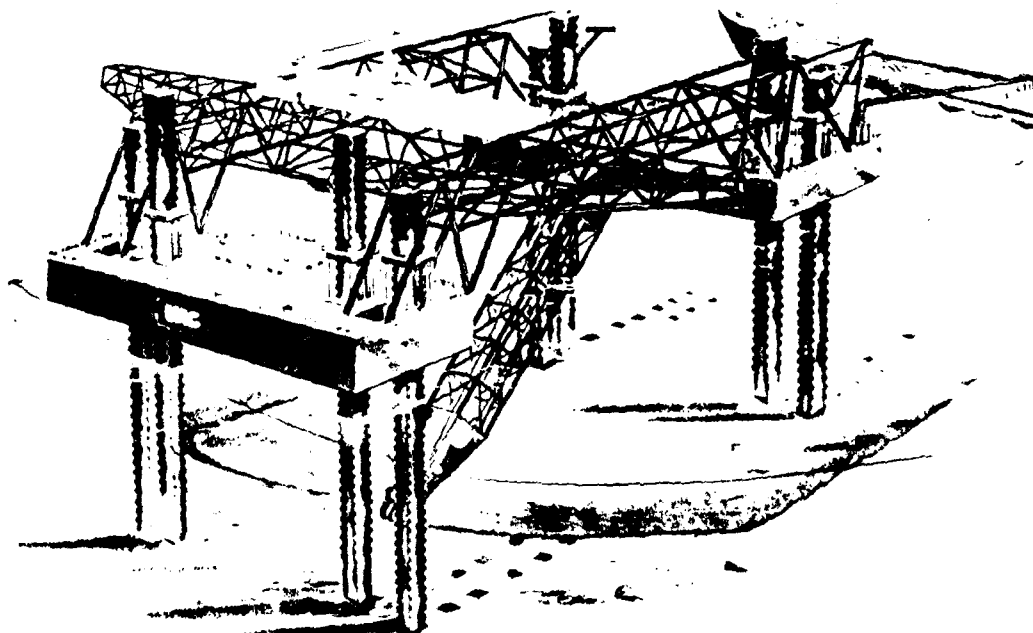
the unit to move in a crawling motion.
The unit stands firmly on the legs
during excavating/dredging and is
equipped with a hydraulically-operated
excavator that can be fitted with back-
hoe, clamshell or dragline bucket. (See
Figure VII-O.) Possible applications
for such amphibian units on dredging
work for maintaining United States
waterways appear to be remote.

(e) SUBMERSIBLE DREDGES: Several sub-
mersible type dredges have been
developed in the United States and
Japan. One of the first such units,
known as the CRAWL CUTTER, was developed
by Ocean Science and Engineering, Inc.
The CRAWL CUTTER was a manned, self-
propelled vehicle electric-powered from
shore that housed a conventional cen-
trifugal dredge pump and was equipped
with a hydraulically-operated cutter-
head much like conventional cutter
suction dredges. It underwent extensive
operational testing on the Atlantic
coast of Florida about ten years ago but
did not demonstrate that it could eco-
nomically serve the pumping intended
(Viz., the restoration of eroded
beaches). Similar type equipment has
been developed and constructed in Japan;
however very little information is
available on its operation or capabil-
ities. In any event, it is considered
unlikely that submersible dredging units
of this type would hve any significant
applications in future dredging in the
United States waterways.

(f) MUD CAT DREDGE: This is a small low-
powered (39 foot long by 9 foot wide)
portable hydraulic dredge with a 8 inch
diameter discharge that is equipped with
a conventional centrifugal dredge pump.
It has a suction head which consists of
a horizontal screw auger mounted on the
end of a hydraulically-operated boom.

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Figure VII-O

Amphibian Dredge (Courtesy IHC Holland)
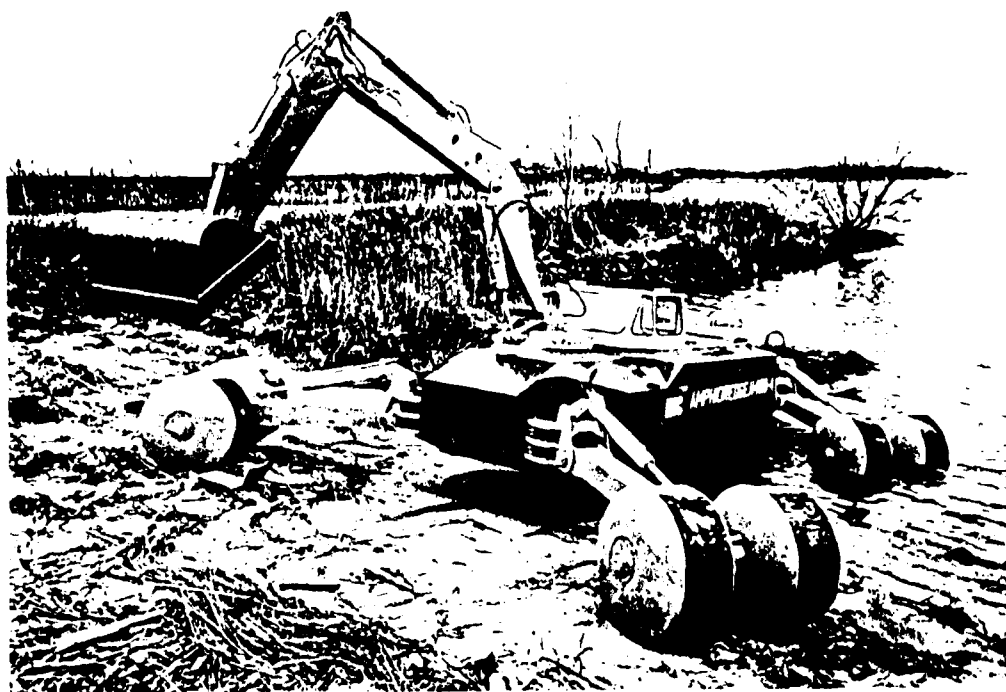
The auger has two halves and the principle of operation is to turn them in opposite directions, thus dredging the bottom sediments to a certan suction. The unit can dredge to a depth of 15 feet and cut a swath 9 feet wide. Dredges of this type are available for lease from the Mud Cat Division of the National Car Rental Service which reportedly has a large fleet of 300 units strategically located in various regions of the United States. (See Figures VII-P and VII-Q.)

(g) AIR CUSHION DREDGES: In 1974 an English firm adapted an air cushion vehicle for dredging and hydrographic surveying work. Cutter suction dredging equipment with a 12 inch diameter discharge was installed, thereby combining dredging capability with the mobility and maneuverability of a hover platform. Little demand for equipment of this type is anticipated in connection with the maintenance of United States waterways.

(h) SIDECASTING DREDGE FOR RIVER DREDGING: A shallow draft sidecasting dredge designed for river dredging applications has been developed by a Dutch engineering firm. (See Figure VII-R.) (Note: The Corps of Engineers currently operates three similar dredging plants for maintaining various shallow coastal bar inlet channels, principally on the Atlantic Coast.)

From the foregoing, it is obvious that there is a significant effort directed towards improvements in all facets of dredge technology. However, if we are to keep pace with the upward pressure on costs attributable to new directions in environmental constraints or the imposition of more rigid requirements, then a dynamic research program will be required so that the necessary technology and eqipment will be available when requirements, whether environmental or otherwise, so dictate. In addition to efforts to improve mechanical and technical components of

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Figure VII-P

(Illustration Courtesy Mud Cat Division National Car
Rental Systems, Inc.)
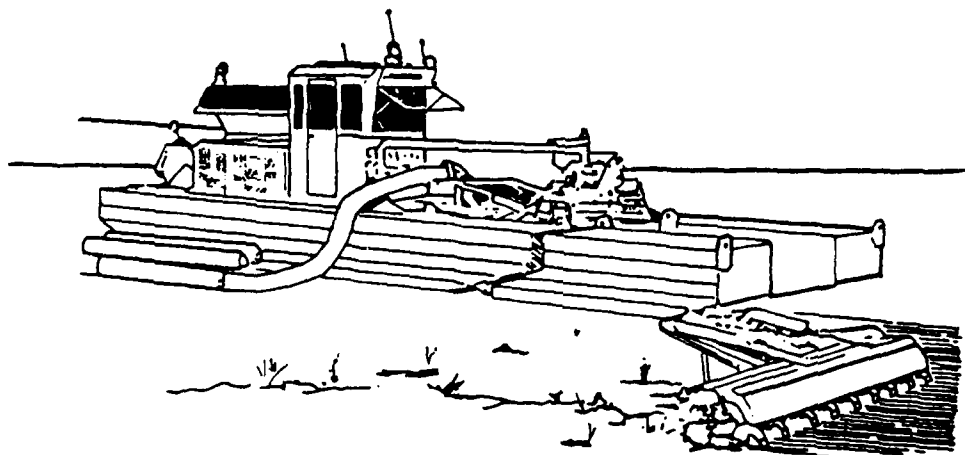
Figure VII-Q

Horizontal Cutterhead of the Mud Cat Dredge showing Cutter
Knives and Spiral Auger (Courtesy of MUDCAT Division
National Car Rental Systems, Inc.)

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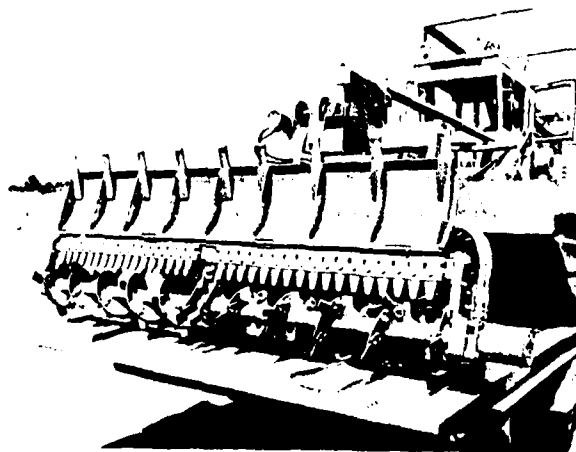
dredging systems, increased emphasis must be given to improving the management of dredging operations. With greater applications of electronics in dredging technology as well as parallel intensive developments in the field of hydrographic surveying, the use of operations research techniques in order to effect efficient dredging methods is expected to become more prevalent.

Figure VII-R

Lightweight Sidecasting Dredge Developed for River Contracts (Courtesy DHV - Holland)
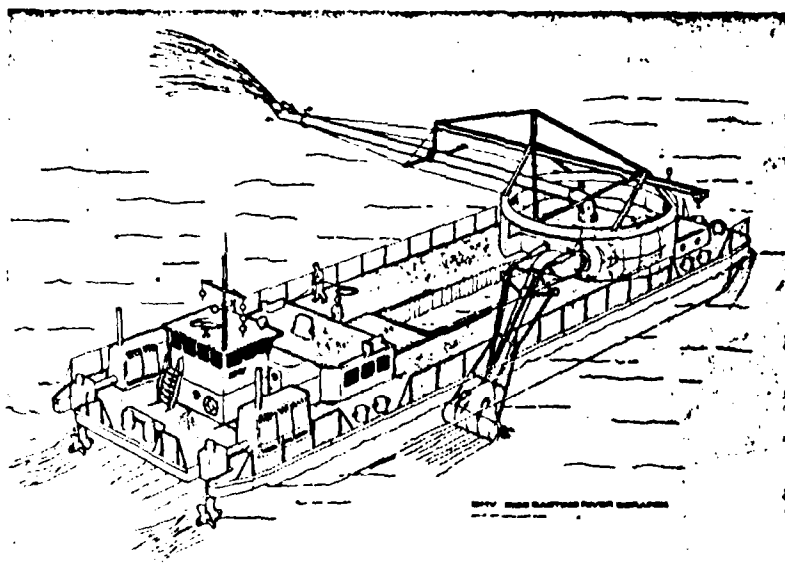
VIII - TECHNOLOGY FOR THE EXTENSION OF
THE NAVIGATION SEASON

The subject of extension of the navigation season encompasses all of the phenomena related to the movement of vessels during winter conditions. Ice can interfere with the operation of locks, impede vessels in channels and open water, erode shorelines and damage structures; and interferes with flow regulations, such as that required on the St. Lawrence Seaway by the International Joint Commission. All of these problems must be dealt with if navigation is to continue into the winter. Navigable waterways of the United States which are subject to these conditions are the Upper Mississippi River System, the Upper Ohio River and tributaries, the Great Lakes/St. Lawrence Seaway (GL/SLS) System, and Western and Arctic Alaska. There are occasional ice problems related to navigation elsewhere in the United States, but their occurrance is relatively rare, and the problems are minor.

The benefits which may be derived from the extension of the navigation season are particularly important in cases where annual waterway traffic approaches the capacity of the waterway without an extended season. Continuing navigation into the winter directly increases waterway capacity and may be an extremely cost-effective way of doing so. The evaluation of season extension programs require a detailed analysis of numerous costs and benefits: the assessment of these costs and benefits beyond the cost of implementing technologies for navigation is beyond the scope of this report.

Although the problems of ice navigation have been studied for the last century, it is only in the last two decades that substantial technological progress in the field has been made. The main body of this section is organized by the three primary areas of winter navigation technology: the operation of locks; navigation in channels and open water; and harbor maintenance and shore protection.

OPERATIONS OF LOCKS IN
ICE CONDITIONS

Ice presents several difficulties to lock operations. Brash ice, floating pieces of ice up to six feet in diameter, drifts or is pushed ahead of vessels into lock chambers and can take up so much of the chamber that vessels cannot enter until the ice is locked through. If a vessel does enter the chamber along with floating ice, the ice is pushed up against the lock walls where it accumulates and effectively narrows the chamber. Floating ice often drifts into miter gate recesses where it prevents the gates from opening fully. Both drifting and frozen-on ice accumulates in the structural niches of lock gates where the buildup may overload the gate sill or prevent the secure closing of the gates. Intake valves are clogged by small pieces of ice, and machinery breaks down more frequently. Ladders and walkways become covered with ice and unsafe for use, as are floating mooring bitts which may freeze in place at the level of the lower pool and then shoot up to the surface of the upper pool unexpectedly. These factors decrease the capacity of locks and increase the hazards and expense of lock operation. The St. Lawrence Seaway (SLS) plan for year round navigation presents a quantitative analysis of the effects of ice on lock operations in the form of a simulation model.

(a)   Ice on or Around
Gates

Valves and gates are the two main moving parts of a navigation lock. Winter operational problems will affect both; however, the gate is exposed to the brunt of the weather. The problems caused by ice are essentially two-fold: one is ice adhering to the gate and causing excess weight, the second is ice restricting the movement of the gate. The first problem is related to cold air temperatures as well as vessels pushing ice into gate structures. The second problem is related almost entirely to moving, floating ice. These problems exist in and have been reported by every Corps district that operates locks in the cold regions from Walla Walla to Huntington. They are perennial problems that occur throughout the entire ice season and that increase lockage time up to tenfold and double maintenance costs.

Several districts have reported problems with ice adhering to and building up on miter gates. When a gate is open, its downstream side is flush with the lock wall and floating ice is pushed into its structural recesses. This, along with freeze-on ice accumulation can overload the gate anchorages due to the weight of the ice. Ice accumulation on the upstream side of the gate, especially in the area where it operates limit switches or where it touches stops in the open position, can keep the gate from fully opening and closing. If limit switch sensors are prevented from being activated, the filling or emptying of the lock may be prevented or delayed.

The lower gate in a high lift dam may be an overhead lift type. When raised, this type of gate cools to air temperature, then when it is lowered, it gets covered with ice. The process is much like old-fashioned candle dipping. The downstream side of the gate is also generally open so that the structural members can collect ice and water. The upstream side of the gate gets a full length coating and unless insulated will continue to build ice when the lock is at high pool elevation. Only a moderate ice cover is necessary to overload the counterbalance and lift mechanism. Another problem is that of ice on the bottom of the gate which inhibits proper seating or closure of the gate and thus allows leakage at the bottom.

The most common actions taken in response to these problems are manual scraping of the lock gates, the use of steam hoses to thaw ice, local heating, and insulation. One study[55] suggests that hollow rubber matting edge seals filled with heated water could be used to prevent ice formation on the matting edges. The same study considered the possibility of heating contact blocks in order to allow miter gates to open fully.

A relatively new technique which is in the experimental stage involves covering the gate recesses with a metal plate and spraying the plate with a polymer coating. The coating reduces the adhesion of ice on the gate. This coating was developed for use primarily on lock chamber walls, and is described in more detail below.

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Floating ice or any debris which finds its way into a miter gate recess prevents full opening of the gate. The usable width of the lock is thus reduced and the gate is vulnerable to damage if struck by a vessel. It is a problem particularly on the upstream lock gates where the ice is drawn into the forebay or lock entrance area by water intakes, and pushed into the gate recesses by downbound vessels. While the problem is more frequently encountered at the upstream gates, the lower gates are also susceptible. When floating ice is present, the difficulties in miter gate operation occur with varying severity at every lockage. It has been reported that the lockage interval under these circumstances is eight to ten times as long as normal.

A common technique, at present, is the hiring of additional personnel who push the ice out of the gate recesses with pike poles. A more sophisticated technique is the use of high flow air screens in miter gate recesses. The design of air screen systems is discussed below, under lock approaches.

(b) *Ice on Lock Chamber Walls*

Ice on lock chamber walls as well as on bitts, floating bitts, and ladders recessed in the walls presents a serious problem to winter navigation. Ice on the walls limits the capacity of the locks simply because it reduces the usable width. The design conditions at the Soo Locks specify a five foot clearance between the lock walls and the sides of vessels or tows although a two and a half foot clearance is common in practice. As the thickness of the ice increases, there is a bottleneck created since ships cannot pass until the ice is removed. For Large traffic it means tows of reduced width or multiple lockages with extra time involved in making and breaking tow.

Ladders and mooring bitts become covered and unusable. Floating mooring bitts have frozen in at the lower pool elevation, and then have shot upward when submerged at a high pool elevation. This type of situation presents a serious hazard to lock and vessel crews.

The floating mooring bitt problem has been circumvented by tying the bitts off at the upper pool level during winter operations. This restricts the vessels to mooring from the top of the wall or using recessed line hooks, where available. In the Union of Soviet Socialist Republics[56] floating mooring bitts are heated, and a small bubbler is installed as well.

The St. Paul, Rock Island, St. Louis, Detroit, Chicago, and Pittsburgh District Offices of the Corps of Engineers have all stated their concern with the problem of ice buildup on lock walls. Each time the lock is cycled a slight coating of clear ice adheres to the walls. In addition, floating ice is pushed against the walls, adheres and forms a much thicker band at the upper level, which can be quite dangerous in high lift locks. In the northern areas this is a constant problem all winter, while as far south as Alton, Illinois, it may last for only a few days. In the past, this icing was removed by scraping the walls with shovels, or poles, or a backhoe. Although slow, expensive and dangerous, these methods are effective. Steam hoses or backhoes are used today to clear ice from chamber walls.

CRREL has developed a specialized mechanical cutting system to remove the ice collar on lock walls. The unit (Figure VIII-A) consists of two parts: a cutting system and a drive and propulsion system. The drive and propulsion system is a 65-hp, 4-wheel drive tractor originally manufactured as a trencher. The cutting system is a three and one-fourth inch wide kerf cutter, manufactured for the coal industry.

When a problem ice collar has built up, the esplanade along the lock wall is first cleared of snow. The tractor is then positioned with the right wheels close to the curbing along the wall so that there is about 1.5 inches in clearance between the wall and the cutting bar. By operating the transmission in third gear and full throttle, a traverse speed of over 10 ft./min. can be maintained while cutting ice collars six to eight feet deep. A quantitative analysis of the design and performance of the saw can be found in the CRREL report "Developments of Large Ice Saws."[57]

Figure VIII-A

Ice Cutting System
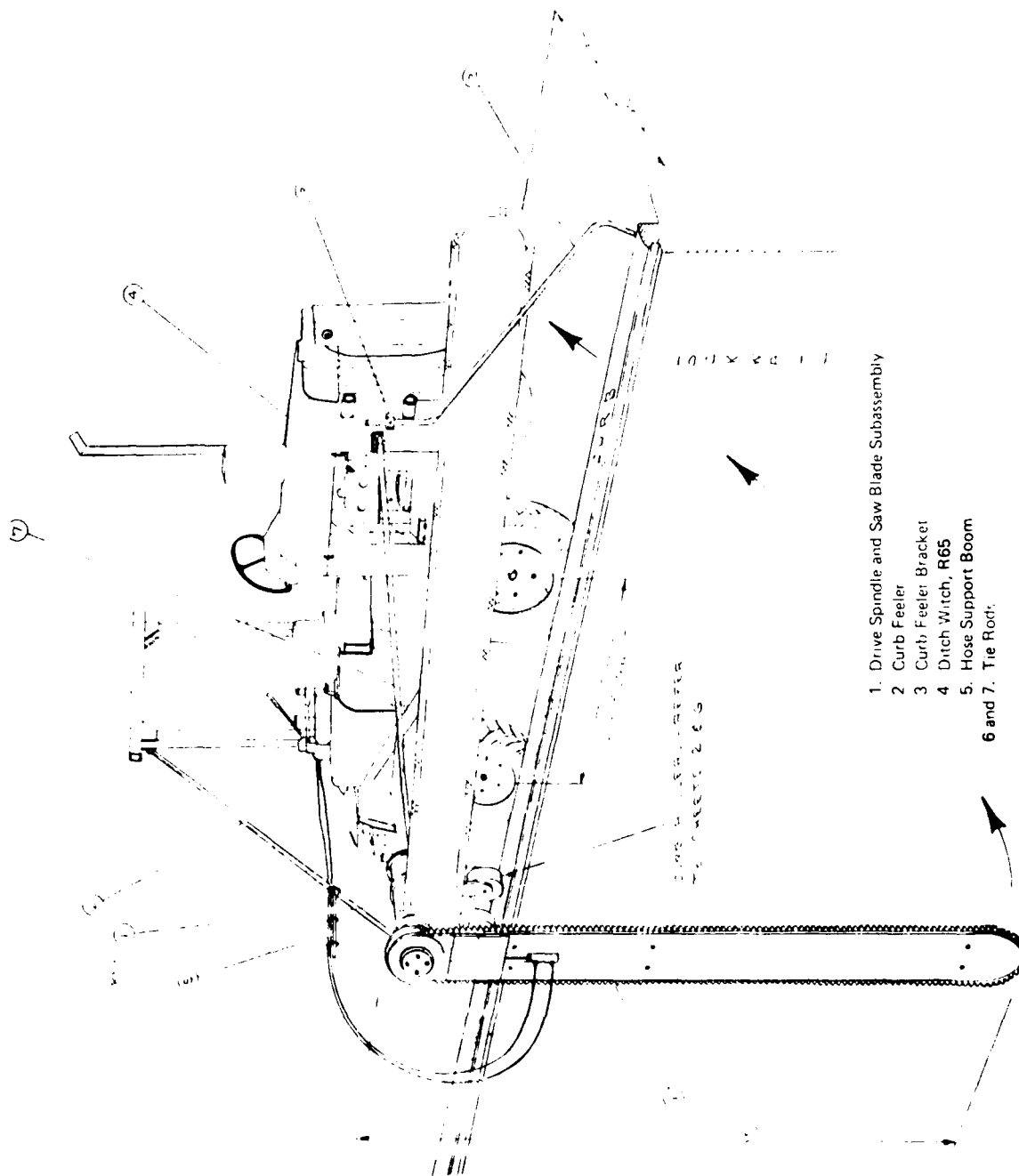
1. Drive Spindle and Saw Blade Subassembly
2. Curb Feeler
3. Curb Feeler Bracket
4. Ditch Witch, R65
5. Hose Support Boom
6 and 7. Tie Rods

Source: Ice Control at Navigation Locks

CRREL has also developed a chemical coating which reduces the adhesive force between the coated surface and the ice that forms on it.

The ideal material would be one which prevented ice formation altogether. The coating developed does not prevent ice formation but it does make the task of ice removal from coated surfaces much easier. The basic material is a long chain copolymer compound made up of polycarbonates and polysiloxanes. The most effective coating of the many that were tested was a solution of the polymer, silicone oil and toluene.

Tests are being evaluated to determine the merits of an undercoating for the copolymer on concrete surfaces that are worn and rough. An epoxy type coating has been used and acts as a filler over the rough concrete. It is hoped the undercoating will provide a better surface to which the copolymer adheres.

Trials of the undercoating and copolymer are being evaluated at the Poe Lock at the Ste. Marys Falls Canal at Sault Ste. Marie, Michigan. Small scale trials are also being studied at Lock No. 4 on the Allegheny River and at the Starved Rock Lock on the Illinois River.

Heating of lock chamber walls to just above freezing point in order to prevent the formation of an ice collar has also been suggested, as have the installation of mechanical devices in walls and the use of high pressure water jets to remove ice; that is at the upper water level to keep ice from adhering to the lock walls has also been suggested. Bubblers have been used to prevent ice formation on lock walls at the Soo. Calkins and Mellor, discuss and cast out several of these techniques. They recommend electrical heating of lock walls, if the capital cost is acceptable. It should be noted, however, that energy costs have risen since their work was performed, and that could affect the analysis significantly. They feel that high pressure water jets are attractive, but expensive and that they involve a technology unfamiliar to lock operators. They dismiss built-in mechanical devices as expensive and unnecessarily complicated. Calkins and Mellor also recommend further study of the coating of lock

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walls with salt solutions, rather than polymers. It has been suggested that those measures which require installation of heating elements for piping in chamber walls may be particularly appropriate for new locks and those undergoing major rehabilitation.

In the Union of Soviet Socialist Republics and on the St. Lawrence Seaway, the water level in the chamber is kept at the upper pool level between lockages, in order to inhibit ice formation.

(c)   Ice Effects on
        Valves and
        Intakes

Despite their general position well below the water surface, intake valves and piping are not free of winter ice problems. Frazil ice, small ice crystals formed in supercooled water, mixes easily in fast flowing water and is carried to depths where it adheres to intake screens, valves and valve seats. Hayes[58] surveys the problem of the optimal location and the detailed design of intakes to avoid clogging by ice. The essence of the location problem is in the inverse of the design of intakes to avoid sediment intake. Unfortunately, the two requirements are often at odds with each other. Where lock valves are located above water, as in flood control projects, a water spray can freeze and adhere to valve guides, stems and seats and thus restrict their usage. To reduce ice on intake screens, the Louisville District only partially opens its intake valves. This keeps ice from being draw down to their intakes, but lengthens filling time and thus increases lockage time, with a corresponding delay in navigation.

(d)   General Ice
        Effects on
        Operation or
        Maintenance

There are a number of separate problems of lock operation and maintenance caused by ice which have been solved by special operational techniques. These problems still exist, however, and since these techniques require time

and money they should not be accepted as an ultimate solution.

Floating ice in the lock chamber often requires a separate lockage. Ice buildup under barges requires the tows to back down before entering the lock to flush out the ice. Normal winter maintenance when there is no traffic due to ice on the river is forced into a shorter time frame. These problems all occur to a varying extent in the St. Paul, Rock Island, Louisville, Chicago, Detroit, and Huntington Districts. They are also found on the St. Lawrence Seaway. Some, like the ice in the lock chamber, are a problem with every lockage; others, like the shortening of maintenance time, are annual.

Floating ice in the lock chamber is locked through, generally separately, but a simple lockage generally does not flush the ice out of the chamber. The Louisville District reports opening the intake valves slightly on one side to flush the lock, while some districts open valves on both sides. Both these methods put water in over the entire length of the lock. On the St. Lawrence Seaway, a single filling manifold at the upstream sill flushes ice very efficiently and also is used to help flush out downbound ships; tugs are used to herd ice from the dead water areas of the chamber. An ice-flushing port system flushes the ice clear of the lock in an estimated ten minutes, greatly decreasing total lockage time required under ice conditions, utilizing upstream sector gates, ice can be flushed out with water flow caused by opening the gates slightly against a full head.

These installations are discussed in more detail in the National Waterways Study Draft Report Analysis of Waterways Systems Capability[59] and the Detroit District's Final Survey Study GL/SLS Navigation Season Extension.[60] Studies have suggested that specialized flow developers installed in the chamber and approach walls might also be used to help flush floating ice more expeditiously. Such flow developers are in use in the Union of Soviet Socialist Republics.

Another approach to the problem of floating ice in the lock chamber is to prevent it from drifting in the first place. A new technique which is becoming more widespread is the use of a high flow air screen in the upstream approach to the lock. The intent is to create a high enough horizontal velocity in the upstream direction to hold back the downbound ice being pushed ahead of traffic.

The air supply available is a limiting factor in the air screen design for optimum flow and vclocity. Parameters affecting the design, once the air supply (volume and pressure) is specified, include: length and size of diffuser line, effective length and size of feeder line, depth of submergence, nozzle size and nozzle spacing.

Such a system was installed at Snell Lock in 1975, at Cote St. Catherine Locks in 1976 and above the Poe Lock at Sault Ste. Marie, Michigan, in 1977.

An air line was tested across the upstream approach to the lock. The line produced a flow pattern which pushed loose ice aside, allowing ships to pass through the lock chamber without pushing large quantities of ice ahead of them into the lock. The installation at Poe Lock is shown in Figure VIII-B.

The air curtain system was also utilized to flush ice from behind lock gates and to reduce ice buildup on approach walls.

The merits of the air screen cited by lock operating personnel, in addition to the reduction in vessel lockage time, were: less wear and tear on lock gate and operating mechanisms and a saving in the time and effort required to remove ice collar buildup on the lock walls. Similar but smaller air screens have been used to keep miter gate recesses clear of ice and debris. It has also been suggested that the air screens might assist in cleaning ice from the bottom of vessels before they enter the lock.

Further model testing of air curtains, such as tests for Cannelton Locks, refined the optimal placement of the

Figure VIII-B

High Flow Air Screen
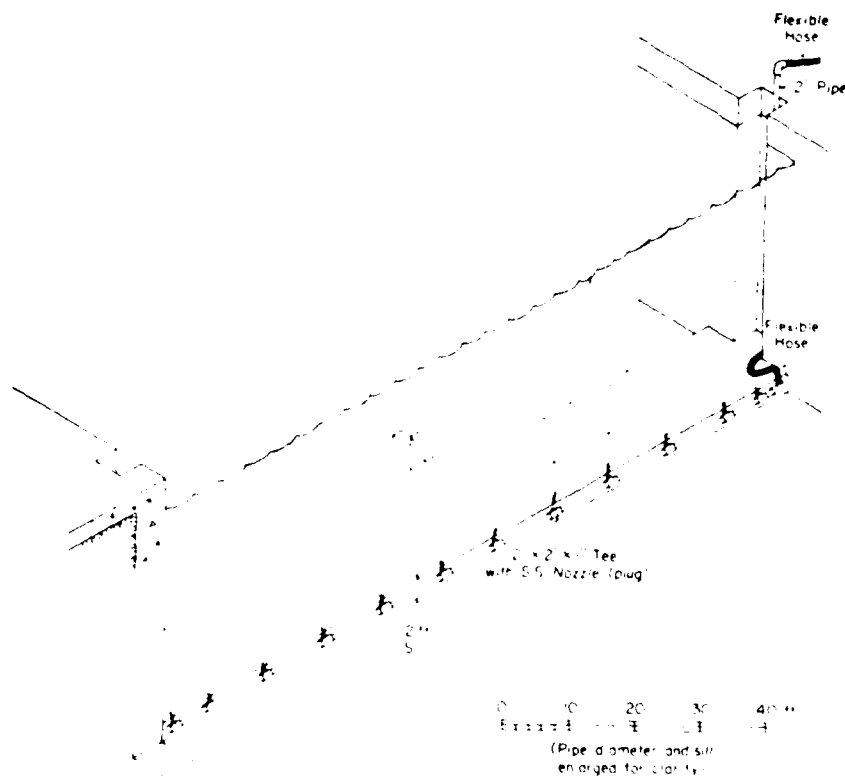
SOURCE: Ice Control at Navigation Locks.

air curtain in the lock approaches. It has been found
that the air velocity systems are most effective during
moderate flow periods; during high flow, the air curtain
cannot resist the fast currents, and during low flow,
little debris or ice is carried into the lock.

The cost effectiveness of air curtains depends on the
percent of time river conditions are appropriate for its
use, and on the level of utilization of the lock.

Other possible methods for keeping floating ice out of
locks include the use of an ice boom, possibly gated, and
flow developers to divert brash ice away from the lock
chamber. Another alternative is the installation of a
diversion channel around the lock; flow developers would
be used to direct floating ice into the channel. The di-
version channel concept is already widely used to prevent
debris from entering the forebay of hydropower plants.

Lock machinery is more susceptible to failure in cold
weather, and thus machinery is often enclosed, heated, or
both, to reduce the frequency of breakdowns. It has been
suggested that extensive preventative maintenance and re-
design of lock machinery is necessary for year-round oper-
ation in areas with severe winter conditions, such as the
GL/SLS. The use of low temperature lubricants may reduce
winter downtime as well.

NAVIGATION IN CHANNELS
AND OPEN WATER IN ICE
CONDITIONS

There are three approaches to the extension of the
navigation season in channels and open water:

1. Ice is prevented from forming.

2. A stable ice cover through which vessels may
pass unassisted is maintained.

3. The ice cover is broken up and vessels navi-
gate through the brash ice.

The following sections describe the techniques which can be used to implement these three approaches.

(a) Prevention of
     Ice Formation

Ice can be prevented from forming by raising the temperature of the surface flow. The additional heat necessary can come from warm effluent or from the warmer deeper layers of the channel itself.

Rivers are commonly used as heat sinks for warm effluent from power plants and other industrial installations. If this effluent is properly diffused into the flow, the formation of ice at the surface can be inhibited. Warm effluent entering at the surface will sink to the four degree Celsius isotherm, the densest layer of water, and will have a reduced effect on surface ice unless it is diffused properly. Ashton discusses the fluid mechanical theory behind the suppression of river ice by effluents and the experimental evaluation of some of the parameters of turbulent heat transfer in navigable channels. Ashton uses the principle of conservation of energy to formulate the governing partial differential equation for the flow. The effect of warm effluent is expressed through a heat flux term in the equation. Heat flux at the water-air, water-ice, and ice-air interface is proportional to the appropriate temperature difference. The constant of proportionality is a heat transfer coefficient which is a function of meteorological parameters when air is involved, the flow regime and properties of water when water interface is involved, and the properties of ice, when an ice interface is involved.

Ashton[61] expands on the criterion used by most theorists for the location of the ice edge. Previous investigators have generally assumed that ice formation begins at the zero degree Celsius isotherm. Ashton suggests that this is indeed the case during periods of cooling air temperatures when there is no prior ice cover present. However, during warming periods, if an ice cover is present and the ice edge is receding downstream due to melting, it will only recede to the location at which the melting from below equals the tendency to thicken from

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above. Thus, a heat balance criterion is used to identify the location of the ice edge under these conditions.

Ashton[62] considers two cases of ice suppression by effluents; in the first and simpler case, the water temperature is assumed to be uniform over the depth and width of the river, implying that the effluent has been completely diffused. This is an appropriate model for an effluent such as a reservoir release. The second case includes the effects of transverse mixing, modeling a side channel discharge of a heated effluent.

Ashton's models were exercized by numerical simulations using finite difference equations. An attempt was made to verify the models through comparison with observations of the Mississippi River near a powerplant in the vicinity of Lock and Dam No. 15, but limitations on the empirical data restricted the extent to which the models could be evaluated.

The (SLS) System Plan includes a mathematical model of the effects of warm effluent based on theoretical approaches which preceded Ashton's. This analysis concludes that in some cases the environmental effect of a substantial inflow of warm effluent would be modest, provided that measures were taken to eliminate hot spots. The effectiveness of warm effluent and the environmental effects depend on the discharge and temperature of the effluent and the flow of the river.

Balanin[63] describes the use of effluent as well as the relatively warm discharge of hydroelectric facilities in the Union of Soviet Socialist Republics. Webb and Blair[64] discuss the use of increased discharge from the Ste. Catherine regulating works on the St. Lawrence Seaway South Shore Canal to retard the formation of ice.

Warmer, denser water from lower depths can be mixed with surface water by using air bubblers in order to suppress ice. Theoretical research and field and laboratory testing of mixing by line- and point-source bubblers has been conducted by Ashton.[65, 66, 67, 68] The melting of the ice cover is governed by the heat balance at the

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water/ice interface. The rate of heat conduction through the ice is modeled by one-dimensional steady-state heat conduction which assumes a linear variation in temperature through the ice and snow thickness together with an estimate of the heat transfer coefficient through the air boundary layer. Bubbler systems of this type have been tested at Duluth Harbor and Lime Island Turn in the St. Mary's River.

The object of the design of such systems is to promote the greatest amount of mixing possible without causing the flow over the entire depth to be reduced to the temperature of the surface.

(b) Maintenance of
a Stable Ice
Cover

Many vessels, especially newer, higher powered ones, can navigate through a stable cover of sheet ice, albeit at slower speed and with lower efficiency. Oceangoing vessels which are intended for service in cold areas are usually ice-strengthened according to classification society rules. These vessels generally sustain only limited damage in the thickness of sheet ice for which they have been designed. Many "lakers," however, are not designed or maintained in class, and some have sustained substantial damage on ice. Modern steel-hulled barges and towboats seem to experience little damage due to ice, although damage may be expected if the boats are of substandard construction. In a 1972 test, a 3600 horsepower towboat successfully pushed conventional barges with 3/8 inch steel hulls through intact ice covers 12 inches thick, with no damage to the barges.[69] General wear-and-tear on towboats and barges does increase during winter service in ice conditions, as does the associated maintenance cost. It has been reported that the maintenance cost of river equipment triples during the ice season.

The critical factor which determines the ability of vessels to navigate unassisted through ice is the maintenance of a stable ice cover.

The most frequently employed means to maintain a stable ice cover and prevent the formation of ice jams is the use of ice booms. This structure consists of floating members extending across the river to catch and hold the ice in place. The floating members are held together with flexible cables which are in turn anchored to the bottom of the river. Such ice booms are relatively cheap and are installed and removed each year. The flow velocity at the surface of the river is slowed to below the critical speed at which a stable ice cover will form. Field experience[70] seems to indicate that a surface-flow velocity less than about .5 m/sec. (1.6 ft/sec.) is required to permit the formation of an intact sheet of ice from frazil accumulations. On the St. Lawrence River, it has been observed that stable ice cover forms mostly when small ice pans freeze together. A criteria widely used on the Great Lakes/St. Lawrence system for limiting velocity for the formation of ice cover is a mean velocity of 2.25 ft./sec. Other research suggests that the number may be a more meaningful criterion for the formation and stability of ice jams and hanging dams.

Winter navigation requires that existing booms installed for the benefit of hydropower production or flood control be modified so that vessels may pass while the stability of the ice cover is maintained. One way to provide a means of transiting ice booms is to install a gate in the boom. The gate may take the form of an opening in the boom with a movable section that is opened and closed for each ship transit, or an opening in the boom without a movable section. In the latter case, it is assumed that the opening is sufficiently small to allow ice to naturally arch across the opening. The time required for the arch to form and the factors on which it depends, such as wind speed, current velocity and ice block size distribution are areas of research.[71, 72, 73]

Since the opening in the boom causes an imbalance in the forces in the cross stream cables, a means must be provided to anchor the force ends of the boom and still provide a clear opening for the ships. Another consideration in the use of existing booms for the extension of the navigation season is that existing ice booms were not intended to withstand the additional forces which might be transmitted to the boom by downbound ships. In addition, some of the existing booms have floating members which are

somewhat unstable under load, and can therefore easily
trip and allow the ice cover to pass over or under the
boom. In such cases, the boom may have to be strengthened
or replaced with a more stable, heavy duty ice boom.

Case studies[73, 74] of the design and performance of
a new gated ice boom implemented for the benefit of navi-
gation provide examples of the state-of-the-art of this
technology. The boom systems described in the studies was
successfully implemented at the head of Little Rapids cut
on the St. Mary's River. In addition, research has been
conducted to study the applicability of navigable ice
booms on the St. Lawrence River between Stillwells Point
and Redmills in the Copeland Cut area.

The loads on ice booms are due to the following
factors:

     1.   thrust against the ice cover from moving ice
upstream.

     2.   friction force of wind.

     3.   hydrodynamic force against the upstream edge
of the ice cover.

     4.   weight of the ice masses parallel to the
water surface and proportional to the slope of the water
surface.

     5.   friction force of the water under the ice
cover.

     6.   load carrying forces of the boom cables.

     7.   tangential forces caused by the friction of
ice against the riverbanks.

These forces are estimated by a variety of empirical
and analytical means.

Model studies are often used in the design of ice
booms as, for example, Burgi[75] and Acres American,

Inc.[76] The evaluation of forces on ice booms is an area of continuing research.

Cost estimates for ice booms for various sites along the SLS may be found in the St. Lawrence Seaway System Plan for Yearround Navigation.[77]

Although traditional ice booms are the predominant form of ice control structure by far, other devices are in use. An archipelago of artificial islands have been built in Lac St. Pierre on the St. Lawrence Seaway. The islands function by grounding drifting ice flows which by freezing together gradually extend the ice cover over larger areas until the entire lake is covered. The rate of formation of the solid ice cover over the lake is thus accelerated by the presence of the islands. Once the ice cover has formed, the islands help hold it in place. Rock filled sunken barges are used by the Corps as ice islands at Soo Harbor.

The system plan for year-round navigation on the SLS indicates that the formation of a stable ice cover is enhanced by deepening and widening the channel. This result is derived by equating the shear stress on the ice cover to the resistance of the ice cover to collapse, the equation is then solved for the equilibrium ice thickness. This thickness is minimized, under the assumption that a stable ice cover is most likely to form when the required thickness is least, by increasing channel width and depth. This result is intuitively understandable, as a larger cross section will lead to slower current velocity for a given discharge, and hence, a stable ice cover is more likely to form.

(c) Navigation
Through Broken
Ice

1. Ice Jams. If sheet ice breaks up into brash ice and begins to move and drift, ice jams will form at bends, bridges, landings, and anywhere else where large pieces of ice are caught up. Ice jams create thick layers and ridges of ice through which vessels cannot pass easily, if at all. They also form hanging dams, which lower

water levels downstream and can flood upstream areas. Hydroelectric power production is also adversely affected by ice jams due to reduced hydrostatic heads and discharge rates.

Ice jams are of concern mainly because of flooding, structral damage to bridges, homes, and other structures, and interference with hydropower production. However, ice jams often impede navigation as well. River navigation has been stopped for as much as 19 days on the Mississippi. Tows have been broken up and barges left adrift in the ice. Great Lakes shipping has often been delayed in the St. Marys and St. Clair Rivers for periods as long as seven days. A report on a simulation model of the SLS[78] points out that ship transits may be stopped completely until the ice cover is reduced to acceptable limits.

The traditional methods of removing ice jams are:

(a) dusting with a solar energy absorbing material such as coal dust or slag in order to speed melting.

(b) blasting.

(c) aerial bombing or artillery shelling.

(d) use of icebreakers.

Melting, even if it is accelerated by dusting is a slow process with potentially adverse environmental effects resulting from the use of energy absorbing material. Blasting, bombing, and shelling not on'y have negative effects on fisheries and river banks, but are not always successful as the broken-up jam sometimes reforms downstream. These techniques have been tried in the United States only in remote areas of Alaska, and are not considered acceptable. Icebreakers have been very successful at breaking up ice jams, especially in the connecting channels which link the Great Lakes. The use of icebreakers is discussed below in more detail.

Another method of dealing with ice jams is the modification of rivers by straightening, deepening, or widening at sites where jams are likely to occur. This has been done succesfully on non-navigable rivers in New

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England and was one of the design considerations when the St. Lawrence Seaway and power project was constructed.

In the Soviet Union, many of the navigable rivers in Siberia have extensive cascades of reservoirs and hydropower plants. Ice jams are controlled effectively by regulating the water levels and velocities. Ice jams may be weakened by changing the upper or lower water levels, or by the release of warmer water from the reservoir. If jams cannot be prevented or removed, discharges are reduced in order to minimize spring flood levels behind jams. The effectiveness of reservoir regulation in controlling ice jams depends on the reservoir length, depth, flow, drawdown volume, and the flexibility to change releases. In one nearly ideal case, 100 kilometers (62 miles) or river is kept open in the spring using warm releases. At smaller reservoirs, ice is broken mechanically and passed downstream in a 100 m (328') wide channel cleared by icebreakers; reservoir releases keep the ice moving. Regulation of discharges is considered the most reliable means of dealing with ice jams on those rivers with regulating works. Russian devices for use on other waterways include: ice cutting machines which cut slots 30-40 centimeters deep at speeds up to 14 kilometers per hour. Prototypes have been tested successfully and could be brought into use. Impulse water jets for destroying ice have been designed by the Siberian Branch of the Union of Soviet Socialist Republics Academy of Sciences. In tests, their working capacity appears to be as high as 6700 m of ice per hour.[79]

The state-of-the-art in the analysis of the mechanics and hydraulics of ice jams both theoretically and experimentally is represented by papers by Kennedy[80] and Tatinclaux, et. al.[81]

2. Icebreakers. Icebreakers are commonly used throughout the world to assist navigation in areas where the ice cover is too thick for vessels to pass otherwise. Such conditions can arise either in sheet ice as a result of severe weather conditions, as in the Arctic and Antarctic, or in brash ice which has been pushed together.

The United States Coast Guard operates a fleet of icebreakers for service on the East Coast, Great Lakes, Arctic and Alaska, and Antarctica. At present, there are no river icebreakers, as such. The icebreaking capabili-

ties of the various classes of United States Coast Guard
icebreakers are shown in Table VIII-1.

Table VIII-1

Icebreaking Capabilities

Cutter/Class	Continuous	Ramming
Type P		
POLAR	6'	21'
GLACIER	5'5"	14'6"
Type A		
WIND	3'2"	11'
Type B		
MACKINAW	2'8"	
DI-I (MOD)	2'6"	9'
Type C		
DI-II	1'6"-1'8"	5-6'
Type D		
WLB	1'4"	4'
WYTM	1'2"	3-4'
WLM	1'4"	
Type E		
WYTL	1'	

NOTE: The ice thicknesses shown are design values for
       clear, blue ice. These are more valid as relative
       indications of icebreaker capability than as abso-
       lute measures of icebreaker performance. Comparable
       data for the new 140' class in service on the Great
       Lakes is not available.

A fleet of icebreakers widely ranging in size is
used extensively in the Soviet Union. Typically, a convoy

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of ice-strengthened cargo ships will be accompanied by a large icebreaker along the Arctic Marine Waterway.

The strategic importance of winter navigation in the Soviet Union has led to the development of exceptionally large vessels such as the nuclear powered "Arktika" class which are far larger than any used by the United States Coast Guard.

A Soviet icebreaker of more economic interest is the "Wartsila" class. This class of icebreaker operates in the approaches to coastal ports and in the estuaries of Siberian rivers. Although designed for operation in ocean conditions, there are limitations on its usage in open water with high waves. Operating in heavy ice, this icebreaker can clear a channel 18 m wide and can break heavy ice jams. In 70 cm ice, these ships can achieve uninterrupted motion at a speed of three kilometers per hour. In ice of 90 cm or more, the ice is crushed by ramming. These icebreakers are equipped with three 1550 kilowatt diesel generators, a 300 kilowatt diesel generator for idling, an emergency diesel generator, and two automated steam plants. This class of ships can be operational in temperatures of -35 degrees Celsius and can be idle in temperatures of -45 degrces Celsius. The crew complement is 24.

Another Soviet class of ship of interest is the ocean-going icebreaker used for convoys in relatively shallow ocean areas and in gulfs. These ships have one deck, two propellers, and nine hull compartments. They are powered by four 1340 hp diesel engines with idling and emergency generators and a steam plant. The specific fuel consumption is 160 gm/hp-hr. Table VIII-2 displays the principal dimensions of these two types of icebreakers.

The primary mechanism used by icebreakers to break ice is the bending of sheet ice to fracture, utilizing the downward force of the ship's weight. The customary bow form of icebreakers, with a raked stem profile and buttocks lines to match, enhances the performance of the vessel in this respect. Ice is also broken through the application of horizontal loads to the edge of the ice sheets: this is less efficient than bending, however. Crushing occurs when the ship first hits the ice, but no useful work is performed. In general the broken ice remains in the channel. A basic area of icebreaking research involves the development of a means of clearing the

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Table VIII-2

Icebreaker Principle Dimensions

	Wartsilla Class Icebreaker		Shallow Draft Icebreaker	
Length	77.6m	(255')	56.19m	(184')
Beam	16.42m	(54')	16.03m	(53')
Depth	4.8m	(16')	6.0m	(20')
Draft	3.26m	(11')	4.2m	(14')
Power to propellors	3700 Kwt (5000 hp)		4100 hp	
Speed in open water	27.7 km/hr (13.9 kt)		14.0 knots	
Operating period	10 days		15 days	

channel of broken ice. No satisfactory method has yet been developed, and this remains an active area of research.

The size of icebreaker required for a particular service depends on environmental conditions and the extent to which the navigation season is to be extended. If navigation is to continue yearround, then a fleet of small vessels would probably be sufficient as ice jams and hummocked sheet ice would be prevented from forming. If, however, the navigation season is only extended for some fixed period, large icebreakers would probably be needed to clear channels at the beginning of the season.

Icebreakers, as such, are not now in use on navigable rivers in the United States (with the exception of connecting channels on the L/SLS). Tows sometimes form convoys and alternate in the lead. Towing companies sometimes designate a towboat as an icebreaker; openwheel towboats are preferred over kort-nozzle equipped boats, as nozzles are said to clog with ice. A practice known as "muletraining" is commonly used on some inland waterways during ice conditions. In this configuration the towboat pushes one barge ahead through the ice and pulls the remainder of the tow in single file behind it. Towboats in service in areas where muletraining is common, such as the Illinois River, have towing knees both fore and aft, in order to take the impact of the towed barges at a sudden stop. It should be noted that the use of a towboat or tow

strictly as an icebreaker is exceptional. Most "icebreak-
ing" is performed by tows as needed to make up their con-
figurations and deliver their cargoes. Tow sizes are gen-
erally reduced relative to normal conditions, sometimes to
one or two barges, because of the limited maneuverability
in ice-clogged channels.

The use on the Mississippi River of a mechanical
ice cutter (MIC) employing three circular saws, mounted on
runners forward of a barge was considered in 1974.[84]
When the barge is pushed into the ice sheet three longi-
tudinal cuts are made. Once cut, the slabs break by bend-
ing under the cutter barge and are deflected laterally
under the adjacent ice sheet by a skeg mounted under the
barge. The result of the cutting pass is an open channel
free of ice immediately behind the craft.

The analysis suggested optimal operating strate-
gies for the use of the MIC to keep channel open for navi-
gation. It is believed that use of the MIC after the rel-
atively short periods of major ice production could enable
navigation to continue for most of the winter season in
the vicinity of Lock and Dam No. 19 on the Mississippi.
Farther north, in the vicinity of Lake Pepin, the produc-
tion of ice occurs for a longer period and would require
more frequent cutting and clearing over a longer period.
The study also concluded that winter navigation will not
increase the natural incidence of ice jamming, nor will
jamming be affected by operation of the MIC, operations
could be specifically planned and directed at preventing
or reducing the incidence of jamming.

Trials of the MIC on the GL/SLS indicated the
cleared channel would refreeze and with each vessel
passing, a new frozen cover with significant brash content
would occur. It was also found that breakage of adjacent
ice cover by vessel waves added to the brash content in
the channel.

A submerged icecracking engine was tested on Mus-
kegon Lake in Muskegon, Michigan. This device breaks up
ice by periodic sudden release of high pressure combustion
gases underneath the ice. An operating form of this de-
vice would be ship-mounted for navigation channel clear-
ance in lakes and rivers. Tests indicated that this de-
vice could clear a channel 40 feet wide through ice two
feet thick at a rate of five mph. A drawback for this type

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of icebreaking device is that it requires a substantial increase in the power supply of the accompanying vessel.

Experiments *were conducted to determine the power* requirements of cutting ice with high pressure water jets. Tests were conducted near Houghton, Michigan, under conditions that yielded ice thicknesses of at least two feet. It was determined that this form of icebreaking was not feasible because it required excessive power plants and the current state-of-the-art for necessary high pressure water jet equipment was not reliable. The reliability of similar Russian equipment described above is not known.

A recent study of the economics of an extended navigation season on the Upper Mississippi[83] states that a 5000 hp towboat and a conventional barge would be needed to maintain year-round navigation in Pool 18. It is believed by Rock Island District personnel that a conventional barge, perhaps ice strengthened, would be sufficient to keep the channel open as long as other traffic was present as well.

The air cushion vehicle (ACV) has emerged as a radical new technology for icebreaking. ACV's hover on an air cushion several feet above land or water and are propelled by fans. During trials of a heavy-duty ACV designed as a transporter for construction equipment in environmentally sensitive Arctic areas, it was noticed that the ACV could be useful in breaking ice. This is accomplished because the pressure of the air cushion transmitted through cracks in the ice actually creates a depression in the water surface under the ice cover (equal in depth to the pressure of the air cushion expressed in inches of water). The ice is thus unsupported by the water in this area and breaks as a cantilever under the weight of the craft. A second ice breaking mode results from the phenomenon which occurs when the ACV achieves a speed greater than the speed of wave propagation (Froude number greater than 1). Then, the ACV generates a single, powerful wave capable of breaking ice.

As a result of tests on the SLS near Montreal and on the Illinois waterway, ACV's have been found to be an effective way of rapidly breaking large volumes of ice. A commercial version of the air cushion platform is available and has been tested on the Great Lakes. Because ACV's cannot move ice after breaking it, they are dependent upon sufficient currents being available to clear

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navigation lanes after the ice is broken. A great deal of care must be taken when using ACV's for icebreaking to prevent ice jams caused by free floating ice. An air cushion device was mounted in a barge pushed ahead of an United States Coast Guard buoytender in trials on the Illinois River. This configuration combined the effective icebreaking capability of ACV's with the ability of the barge and tender to push the broken ice out of the channel. A possible future application of ACV's is the breaking of ice as it forms near banks, groins, and dikes. The broken ice would be carried downstream before an ice cover could form over the navigation channel. The basic problem with all ACV's, including the air cushion platform, is the high level of maintenance required of the skirts, which contain the air cushion under the vehicle.

3. Alternatives to Icebreaking. An alternative to the use of large icebreakers to escort or clear channels for deepwater cargo ships is the development of cargo ships which can traverse severe ice conditions unassisted. The feasibility of using modified cargo ships in Arctic conditions was initially established by the full scale tests of the S.S. Manhattan, a 145,000 dwt tanker. The Manhattan trials, cargo carrying ships icebreaking bow and additional hull strengthening, and was sent through the Northwest Passage to Alaska. On the basis of data collected during the Manhattan trials, cargo carrying ships capable of moving continuously through seven feet of ice have been designed. A fleet of 350,000 dwt tankers is currently planned by the Globtik shipping group to operate through the Northwest Passage.

If ice does not completely cover the waterway, then ships need not have the usual icebreaker bow configuration. In fact, the "ice cutting" bow as opposed to the "ice breaking" bow is an advantage in conditions where floe ice is soft and not under pressure as this form enables the vessel to have an open water form more suited to good seakeeping performance, less slamming, better directional (coursekeeping) control and better dead weight ratios. However, the "ice cutting" bow is entirely unsuited to severe pack ice or solid ice conditions and vessels fitted with this bow form would have to limit their operations in ice to southern regions of the North and moderate seasons. For such vessels the environmental conditions are unlikely to demand significant hull form departures from the conventional.

German and Dadachanji[84] discuss existing and potential hull forms for ice cutting vessels. The primary consideration in the hull designs of these ships are one, that the specific area of operation and operating season must be carefully weighed in order that the vessel shall neither be over designed nor under designed to its capability requirements, and two, that resistance to motion in the design ice conditions be minimized.

Another alternative is the use of warping or kedging systems to assist vessels through ice-clogged channels. A report by Mellor[85] outlines ten possible operational concepts. Mellor also analyzes the crushing resistance of ice, in order to estimate the force requirements for warping or kedging systems in terms of thrust augmentation for existing vessels. No such systems are currently in use.

Under SLSDC guidelines, the duration of vessel operation during ice conditions is related to the criteria of vessel capability. The higher the critical ratio of horsepower to length, the longer the vessel is permitted to operate.

4. Navigational Aids. Conventional navigational aids, mainly buoys which mark the locations of navigable channels and hazards to navigation are generally removed before the formation of ice and replaced after the ice has melted in order to avoid damage. Yearround navigation, not limited to daylight and clear weather, would require the installation of fixed lighted aids at shoals, and as ranging lights. Electronic position-finding equipment such as the mini-Loran C installed experimentally on the GL/SLS or satellite navigation systems can provide very high accuracy position location regardless of visability. The P.I.L.O.T. system in use on the St. Marys River utilizes a chain of Loran C station and sophisticated receivers installed aboard ship. The receiver comprises a Hewlett-Packard microprocessor and a cathode ray tube (CRT). The CRT presents a diagram showing the location, heading, in-channel and cross-channel speed, and past and future track of the ship. In critically narrow reaches, the system is accurate to within 25 feet. Because of the geometry of the Loran C transmitting stations, accuracy drops off in other reaches where precise locations is not so critical. A hand held receiver which indicates only position is being tested as well. The addition of radar

reflectors to existing navigational aids is an inexpensive and effective improvement.

The Coast Guard has evaluated radar transponder beacons (RACON). The RACON is designed to transmit a response to a ship's radar signal, enabling long-range detection of a shore target and better range determining capability.

The range enhancement is a significant factor for safe navigation during an extended season because ridges caused by windrowed ice can create a false display of the shoreline, thereby introducing position uncertainties. RACON displays on ship radar screens indicate the bearing and range to the unit and the signal can be coded for positive identification. Detection ranges averaged eight to 16 miles, depending on the type of ship's radar.

The Maritime Administration contracted for the study of a precise all-weather navigation system to evaluate several alternative navigation configurations for use in restricted navigation waters.

The objectives of the test program were to acquire engineering data, verify system operation, analyze operational constraints on shipping, and to assemble information pertinent to the specific needs of a Great Lakes all-weather navigation system design. The contract called for the design and construction of a hybrid shipboard radar/laser precise navigation system which would consist primarily of laser and radar transmitter/ receivers.

Optical and radio-frequency ranging techniques were utilized, employing both a pulsed laser and a pulsed radar as inputs. A computer, an ultra high speed interval timer and various signal conditioning and control circuits were integrated to provide real time information pertaining to the vessel's position and attitude in the narrow channels. The output displays the distance to the next turn, the distance, right or left of the channel centerline, the angular difference between the vessel's heading and the centerline of the channel and the true speed over the bottom.

The evaluation of the experimental precise navigation system demonstrated the ability of a computer-controlled system to automatically produce accurate real-time navigational data for a continuous series of courses through restricted waters. Observations indicated that a practical, all-weather, precise navigation system can be produced utilizing a dedicated radar integrated with a mini-computer.

The Coast Guard investigated a system for ship guidance in channels, harbors and other waterways using a magnetic field generated by undersea cables. The purpose of the investigation was to discover a short-range, high-accuracy system which would not be affected by high winds and ice. Such a system could substitute under certain limited conditions, for buoys, which are easily damaged at dry dock stations by severe winds and ice.

The wire guidance system consists of an electrical conductor deployed at the bottom of a waterway, along a prescribed course or channel. The water is energized with a low frequency alternating electric current. The magnetic field created around the wire is detectable by using a wire coil. Two such coils are mounted perpendicular to each other and are applied to the vertical and horizontal deflection plates of an oscilloscope, generating an elliptical figure.

The figure on the oscilloscope rotates in accordance with the lateral position of the craft coil with respect to the wire. This phenomenon allows a vessel with properly installed system to accurately follow the course of the wire installed on he bottom.

The essential feature of the sensing system was the fact that the vertical component of the magnetic field vanished at points directly above the cable, which was an indication of desired postion. The results of the follow-the-wire investigation were sufficiently promising to warrant further investigation leading to a prototype installation. Successful field trials led to the design of a wire guidance system for Whitefish Bay.

Although a system was designed, it was never tested as it was determined that this system was not as effective as Loran-C and others.

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The Coast Guard designed and constructed an experimental single station laser range light consisting of a one million candle power laser and an eight inch diameter focusing lens. It was installed on Neebish Island to cover Lake Nicolet Channel in the St. Marys River.

The laser range differs from a conventional range light system in that the observer does not have a direct view of the light. A very narrow light beam is aimed above the vessel and is visible due to a scattering of the light beam from minute dust or precipitation particles. The beam appears sometimes like a trolly wire in the sky, providing an accurate lateral alignment of the vessel within the channel. The laser beam could be seen clearly under clear to hazy atmospheric conditions, however, the beam was not used under heavily overcast conditions.

The laser range light was found not to be usable during daylight hours; however, it was extremely visible at night. Ship operators reported the system may be too sensitive for midchannel use. While it was possible to position a vessel under the beam, a person on either bridge wing of a large ship could get the impression that the ship is far off the beam. Further research is required to determine the usefulness of the beam under varying atmospheric conditions and what the optimum requirements of the physical components of the system for all-weather use would be.

The Coast Guard is also developing buoys which can remain in use throughout the year. Experience indicates that substantial reserve buoyancy and special moorings are required to meet demanding winter conditions. A fluked anchor, in addition to a concrete block, is necessary in most locations. Cost estimates for these improvements may be found in reference (1).

5. Ice Forecasting and Surveillance. The major problems related to ice information are the lack of detailed documentation of ice-cover formation, movement and decay; insufficient operational data on ice and weather conditions for shipping interests, and the absence of accurate short and long range forecasts of ice conditions which are necessary to permit advance scheduling of ships. Actions taken to address these problem areas have included aerial surveillance; the monitoring of such parameters as air and water temperatures, water levels and

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flows in restricted channels, and ice thickness; and the development of forecast and dissemination techniques.

The Great Lakes Environmental Research Laboratory (GLERL), a component of the National Oceanic and Atmospheric Administration, is the lead agency of the GL/SLS Ice Information Work Group. GLERL has utilized surface and aerial reconnaissance including ice thickness and temperature measurements, and bathythermographic measurements in order to determine ice thickness movements and effects on navigation. The National Weather service provides warnings wind, weather, waves, storms, and ice covers on the Great Lakes. The United States Coast Guard provides aerial reconnaissance and ice sampling services through fixed and rotary wing aircraft, using both visual means and side looking airborne radar (SLAR) systems. A different, but related radar system used for remote sensing of accumulated frazil and brash ice is described by Dean. This data has been utilized in the development of short and long range ice forecast techniques, including long term freezeup and breakup predictions for GL/SLS harbors and channels.[87]

At present, the Ice Navigation Center in Cleveland keeps abreast of commercial shipping itineraries and the plans of all Coast Guard icebreakers; schedules Coast Guard ice reconnaissance; collects and disseminates ice information to interested users; and validates and transmitts remote sensing imagery to Coast Guard shore stations for broadcast to merchant vessels.

The Ice Navigation Center produces the ice summary which is issued approximately three times a week. In addition to the ice summary, the latest ice forecast and outlook issued by the National Weather Service was relayed by the Ice Navigation Center for broadcast from Coast Guard shore stations. The ice summary is passed to all districts and mailed to vessel agents. A high resolution telecopier network enables the transmission of remote-sensing imagery and ice charts to the National Weather Service, Detroit, and Ice Forecasting Central in Ottawa, Canada. An information package, continuing remote imagery, ice charts, daily ice summary, and wind/temperature charts, is made available to vessels transiting the Soo Locks. This package enables ship operators to plan their routes to avoid the worst ice conditions and to take advantage of any less severe conditions. In addition, hourly NOAA sattelite photographs of the GL/SLS are

available. Soviet convoys traversing the Arctic Marine
Waterway receive very similar data from ground stations
and an extensive fleet of specially designed planes and
helicoptes with short runway requirements and skis. Some
of the ships and larger icebreakers carry planes and heli-
copters which take off and land on their decks.

The Coast Guard has begun a program of tagging
icebergs with transmitters which can be detected by recon-
naissance satellites, easing the load on aircraft. A SLAR
system with computer enhanced imagery is being developed
to assist in the location of icebergs. The SLAR system
also was developed for ice reconnaisance and applied op-
erationally in the Great Lakes through the efforts of
HASSA-Lewis and the United States Coast Guard.

The United States Army Corps of Engineers Ohio
River Division (ORD) has developed a waterways information
reporting program for the Ohio River and tributaries which
has potential for application on other waterways as well.

The ORD program was initially developed in re-
sponse to a need for real time information on the status
of the waterway routes during the severe ice conditions
experienced in the winters of 1978 and 1979. The waterway
carriers and federal agencies providing services to the
waterway users found the data valuable in connection with
scheduling of equipment and personnel. Coordination of
ice management activities was also expedited.

From the original intent as an ice report, the
ORD method evolved as a continuing year around report on
navigation conditions throughout the Ohio River system.

A portion of, the report for January 21, 1980, is
shown in Figure VIII-C. This is a sample of a report that
is generated during normal conditions. It lists the mile
of the Ohio River, the name of the lock or the location of
the information, the date and time, the gage readings of
upper and lower and the change within the last 24 hours.
It also lists the dam condition. This is an indication of
the amount of flow and the position of the navigable pass
dams. The air and water temperatures are shown as well as
the amount of precipitation and an indication of the weath-
er conditions. Lockage information is also provided. This
information is as of the time shown or within the last 24
hours, as appropriate. The wait AB and the wait BL is the
number of tows presently waiting above locks or below the

Figure VIII-C

ORD Navigation Information System Report

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**************************************************************************
**************************************************************************
                        OHIO RIVER DIVISION
                INFORMATION ON NAVIGATION CONDITIONS
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	OHIO RIVER	DATE	HYDROLOGIC CONDITIONS	DAM	WEATHER		WAIT		LOCK		COMM. TOWS AVG
MILE	LOCK/DAM	TIME	GAGE/CHANGE	COND	TEMP	PRECIP	AB	BL	UP	DN	DELAY
5	EMSWORTH	800121	U1 6.0 +0.1	22	A26	0	CL 0	0	10	9	0
		0700	L15.1 -0.7		W37						
13	DASHIELD	800121	U15.0 -0.6	--	A22	0	PC 0	2	9	9	0
		0700	L15.2 -0.7								
31	MONTGMRY	800121	U12.0 -0.1	18.5	A23	0	FA 1	0	11	8	01:08
		0700	L13.5 -0.7								
54	NEW CUMB	800121	U12.0 -0.1	19	A25	0	FA 0	0	11	8	0
		0700	L14.7 -0.8								
	800121 0700 LARGE LOCK BACK IN OPERATION!										
84	PIKE IS	800121	U12.1 -0.1	17	A25	0	FA 0	0	5	8	0
		0700	L14.9 --0.8		W38						
125	HANNIBAL	800121	U11.9 +0.1	16	A22	0.0	FA 0	0	7	6	0
		0700	L14.1 -0.1								
162	WILLOW I	800121	U12.2 NC	20	A20	0	FA 0	0	7	7	00:08
		0700	L16.3 -.2		W38						
204	BELLEVIL	800121	U12.2 -.1	25	A26	T	FA 0	0	8	6	00:00
		0700	L15.2 -.5		W36						
238	RACINE	800121	U12.5 +.1	27	A23	.04	FA 0	0	8	6	00:07
		0700	L17.4 -.7		W39						
279	GALLIPOL	800121	U12.2 +.1	60	A22	0	FG 0	1	8	7	01:20
		0700	L26.1 -.6		W41						
341	GREENUP	800121	U12.2 +.1	82	A22	T	FA 0	0	9	11	00:04
		0700	L30.5 +.6		W40						
435	MELDAHL	800121	U12.1 -.1	86	A24	T	FG 0	0	3	8	00:03
		0700	L29.0 +2.4		WMI						
	800117 0700 AUX. LOCK CLOSED FOR REPAIRS TO UPPER MITER GATES.										
471	CINCINAT	800121	L13.9 NSS		A18						
		0700									
532	MEL LAND	800121	U12.2 +0.2	65	A18	0	CL 0	0	5	5	00:00
		0600	L27.9 +1.7		W38						
607	MCALPINE	800121	U12.2 -0.1	85	A24	0	FR 0	0	7	6	0
		0600	L27.9 +0.8		W--						
721	CANNELTN	800121	U9.1 0	85	A25	00	FA 0	0	2	12	00
		0600	L21.5 -0.5		W40						
776	NEWBURGH	800121	U10.1 -0.1	189	A24	00	FA 0	0	2	11	00:00
		0600	L26.4 -0.9		W--						
792	EVANSVIL	800121	U14.0 -0.8		A--						
		0600									
846	UNIONTWN	800121	U12.2 +0.2	17	A	0	FA 0	0	2	11	0
		0600	L23.2 -1.3		W42						
877	LOCK 50	800121	U25.6 -1.0	DWN	A27	0	FA 0	0	4	11	0
		0600	L---- ----		W--						
903	LOCK 51	800121	U26.0 -1.0	DWN	A28	0	PC 0	0	5	14	0
		0600	L---- ----		W--						
	800121 0600 FALLING 1/4										
935	PADUCAH	800121	U24.6 -0.7		A--						
		0600									

locks. The column headed "lock-up and lock-down" is the number of tows that have locked either up through the locks or down through the locks within the last 24 hours. Column headed "average delay" is the average delay per locking two experienced within the last 24 hours. Other narrative information can be added as required; i.e., this report indicates that the large lock chamber at New Cumberland is back in operation. It also indicates that the auxiliary lock is closed for repairs at Meldahl.

During actual ice emergencies, Figure VIII-D, the report is expanded significantly. Narrative information can be added at the locks or in general verbal notes at the end of reports. Copies of reports during ice conditions are shown in Figure VIII-D. A code for the ice condition is printed on each report.

Long term ice forecasting is a subject of research around the world. Thickness of winter ice is a function of three interrelated factors:

(a) Growth of ice from below due to heat losses into the atmosphere.

(b) Drift of ice away from the study area, and the invasion of ice from other areas.

(c) Formation of new ice on open water arising as a result of drift and hummocking.

The evaluation of these factors in the Soviet Union is based, to a great extent, on meteorological forecasts. In the Soviet Union, these forecasts are compiled by the Arctic and Antarctic Institute on the basis of the macrocirculatory, synoptic method of Vangengeim and Girs. The application of this technique has not been successful in the eastern Arctic because the macrocirculation method cannot forecast anomalies in air movements in a particular region, not only with respect to wind speed, but with respect to direction as well. Sancevich[88] describes the shortcomings of the methods presently in sue and discusses several alternatives, including the application of recent geophysical research on the effects of solar radiation on atmospheric circulation and the correlation of the cycles of cosmic phenomena such as solar activity, lunar tidal

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Figure VIII-D

ORD Navigation Information System Report During Ice Conditions

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                        OHIO RIVER        790208
                     LOUISVILLE DISTRICT
               INFORMATION ON NAVIGATION CONDITIONS
                              HYDROLOGIC CONDITIONS      CONT. TOWS
                                            TEMP    WAIT LOCK
   MILE  LOCK-DAM DATE-TIME    UG    LG    DAM AIR WATER AB BL UP DN DELAY
   471   CINCINN
   532   MARKLAND 790208 0600 12.6 16.9    5   0   35    0  0  8  7  0
   607   MCALPINE 790208 0600 12.3 15.    15   5   -     0  0  8 11  0
   626   KOSMOS   790208 0600 ---
   721   CANNELTN 790208 0600  9.0 14.7   33   2   -     0  0  8  7  0
   776   NEUBURGH 790208 0600 10.0 18.8   41   0   -     0  0 10  7  0
   792   EVANSVLL 790208 0600 17.6
   846   UNIONTWN 790208 0600 12.0 17.4   48   0   35    1  0  9  6  0
   877   LOCK 50  790208 0600 17.7 ----   DUN  -6  --    0  0 13  9  0
   903   LOCK 51  790208 0600 18.4 --     DUN   7  --    0  0  9  5  0
   935   PADUCAH  790208 0600 16.3
   939   LOCK 52  790208 0600 20.1 --     DUN   7  34    0  0 10 17  0
   963   LOCK 53  790208 0600 25.0 --     DUN  11  34    0  0  8 14  0
   980   CAIRO    790208 0600 23.8
SPECIFIC LOCK NOTES
CINCINN   790208 4241 INFORMATION UNAVAILABLE
MARKLAND  790119 0702 AUX. LOCK CLO. UNTIL FURTHER NOTICE
MARKLAND  790207 0655 HYDRO 3 U, 32,500
MARKLAND  790208 0654 WEATHER .18/CLO 4.0SC .58WC
MCALPINE  790131 0756 HYDRO PLANT RUNNING 8 UNITS
MCALPINE  790208 0734 WEATHER 0/PC   3.5 SC   .36 WC
KOSMOS    790201 0805 KOSMOS GAGE NOT WORKING
CANNELTN  790208 0736 WEATHER 0/FOG 4 SC  .42 WC
NEUBURGH  790205 0520 BRG. LOCATED ML 771; SLV. OP. ON M/V ML 769 RESUME
NEUBURGH  790208 0754 WEATHER 0/CLEAR 3" SC .30 WC
UNIONTWN  790208 0509 WEATHER  0/CLY  3"SC .18WC
LOCK 50   790208 0511 WEATHER  .15/CLR 4-1/2"SC  .45WC    F 1/3
LOCK 51   790208 0807 WEATHER  .09/PC   4.0 SC   .35 WC   F-1/2
PADUCAH   790208 0809 WEATHER  .16/PC
LOCK 52   790208 0810 WEATHER  .06/CLEAR  5.0 SC  .49 WC  F-1/2
LOCK 53   790208 0812 WEATHER  .05/CLEAR  2.5 SC  .22 WC  F-1/2
                     ICE REPORTS              HYDROLOGIC COND
LOCK-DAM DATE      REPORT    REMARKS          UG    LG    DAM
MARKLAND 790208 9A1/8CX   N                  12.6  16.9    5
NEUBURGH 790208 3P1SX      NONE              10.0  18.8   41
                     SUMMARY OF CODES
  ELEMENT 1      ELEMENT 2      ELEMENT 3  ELEMENT 4    ELEMENT 5
  AMOUNT         TYPE           THICKNESS  STRUCTURE    EXTENT
  0-NONE         R-RUNNING      IN INCHES  B-BREAKING   IN MILES
  1-SCATTERED    A-STATIONARY              H-HONEYCOMBED UPSTREAM
  2-2 TENTHS     P-STOPPED                 T-ROTTEN
  3-3 TENTHS     J-JAMMED                  L-LAYERED
  4-4 TENTHS     F-FORMED LOCALLY          C-CLEAR
  5-5 TENTHS     S-SHORE
  6-6 TENTHS
  7-7 TENTHS
  8-8 TENTHS
  9-9 TENTHS
 10-FULL
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forces, rotation of the earth's axis, and the speed of rotation of the earth with long term weather patterns.

Predictions of ice formation and breakup on the GL/SLS are based on heat balance models and are reported to have been accurate to within several days. The freezing model for the GL/SLS is in use and the break up model should be operational in the near future. Ashton[89] suggests that the most useful practical heat balance models for forecasting apply a constant heat transfer coefficient to the difference between the water temperature and the air temperature. While incorrect in principle, since certain of the components of the heat balance depend on factors other than the air-water temperature difference, this simplification is expedient and often yields acceptable predictions. Accuracy is increased if the radiation components, wind effects, and evaporation effects are included. The most acceptable compromise may be the empirical determination of the seasonal variations of such heat transfer coefficients by analyzing past meteorological data in detail, say, on a monthly basis.

6. Effects of Ice on Channel Maintenance. The effects of ice on channel maintenance consist primarily of interruption or complication of dredging activities. The difficulties range from damage to dredge pipelines, loss of dredging buoys caused by floating ice, and protection of the floating plant during icing conditions, to interruption or delay of dredging activities until after the period of ice.

Where the winter season is long, the interruption of channel maintenance is complete. To the extent that dredging personnel can otherwise be utilized, little loss occurs as a result of the interruption, and some of the time can profitably be used to perform periodic maintenance on the dredging equipment. When the interruption is irregular, the delays may be more costly, and disruptive to schedules. The dormant period of no dredging during ice conditions also increases the cost of equipment in the sense of limiting the active period of usage of a large capital investment in equipment. In some cases this is circumvented by scheduling dredge usage in ice-free (generally southerly) reaches during wintertime periods. There is some evidence that the increase in vessel power required in ice conditions may exacerbate propeller jet scouring of the bottom and increase deposition downstream. Additional dredging may then be necessary, either

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as remedial maintenance or overdraft in advance of the winter.

7. Operational Safety During Ice Conditions. Safety measures which reduce the chance of personnel falling overboard, or which enhance survivability in the water and prevent loss of life and property are critically important in ice conditions because of the short survival time in cold water and the difficulty of finding overboard personnel in bad weather.

The GL/SLS Navigation Season Extension Demonstration Program[90] has:

(a) tested portable hand-held radar transponders which enhance the aerial detection of small survival craft; the transponders can be detected from a distance of 16 miles at an altitude of 1500 feet.

(b) performed a feasibility study to identify the man-overboard alarm system with the greatest potential.

(c) participated in the development by the Naval Air Development Center of a constant wear exposure jacket.

(d) distributed new radar transponders to several ships.

(e) evaluated Emergency Position Indicating Radio Beacons.

(f) studied means of improved group exposure protection.

(g) studied the added stress factors to which personnel participating in winter navigation are subjected.

(h) investigated enclosed survival craft capable of being launched with all personnel aboard.

During ice conditions on inland waterways, deckhands are usually restricted to the inboard gunwales of

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tows to reduce the chance of falling overboard into freez-
ing water, and tow pilots will ferry deckhands in a light
boat while making up tows, rather than forcing them to
walk along an outboard gunwale. Life preservers are worn
by deckhands at all times throughout the year.

The Coast Guard has sponsored original research
on hypothermia and its treatment.

HARBOR MAINTENANCE AND
   SHORE PROTECTION IN
   ICE CONDITIONS

The dates of the navigation season are largely deter-
mined by the availability of harbors. Sheltered harbors
will freeze before open water, and all of the structures
associated with ports provide potential ice jam sites.
Vessels are also limited by the size of the harbor ap-
proaches in their ability to seek the path offering the
least ice resistance.

Both the shore and structures projecting from it are
affected by ice. The loading placed on structures by
stationary ice is severe enough, but extension of the nav-
igation season causes sheet ice to be broken up and floes
set adrift. Moving ice floes impose tremendous loads on
docks, especially small boat facilities, and on piers,
breakwaters, and the shore.

Residents of islands in navigable waterways are accus-
tomed to using the winter ice cover as a bridge to the
mainland because it is capable of supporting snowmobiles
and even cars. Extension of the navigation season has
both disrupted the solid bridge and created difficulties
for ferries, because of the drifting floes; natural con-
ditions can also be responsible for ice floes which cause
difficulties for ferry operation.

(a) Harbors

Three major types of ice afflict harbors on the GL/SLS:

1. Ice formed on open lake waters and transported by winds and currents into outer harbor areas.

2. Wind blown ice entering the inner harbor areas from the outer areas.

3. Solid ice formed along docks and berthing areas. The effects of ice include, when navigation is not stopped completely, damage or forced removal of auxiliary structures such as ladders and handrailings, floats, and small docks, and difficulties of access to docking areas when a solid ice cover exists.

Bubblers are often used to keep ice from forming at piers, and high pressure water jets and steam hoses are used to remove ice which has accumulated.

Coast Guard ice breaking is needed in harbors because drifting ice tends to accumulate in sheltered harbor areas and because the area available to vessels for maneuvering can easily become restricted by the combination of harbor limitations and ice. Harbor icebreakers are generally smaller than those used in open water, and are often described as icebreaker tugs. These vessels clear ice out of navigable channels as soon as it forms or drifts in, and hence do not have to deal with thick accumulations of hummocked ice.

Cargo handling technologies must be able to function in ice conditions. The development of taconite, a non-freezing form of iron ore, permitted the shipping of one of the most important commodities on the Great Lakes to continue year-round. Coal hopper cars are typically placed in electric, propane, or oil fired thaw sheds immediately before their contents are dumped. However, the problem often persists and the coal either sticks to the inside of the hopper car or falls out in huge, frozen lumps. Without adequate thawing equipment, this situation can cause tremendous delays in the unloading of trains and the loading of vessels.

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To combat this problem there are at least two interesting developments which bear mentioning. The so-called Galloping Gertie, installed by Chessie at Newport News, Virginia, and Curtis Bay, Maryland, consists of a series of multi-fingered vibrating probes, installed at the dumping pump to ensure that frozen lumps are broken into manageable proportions. The powered probes are forced down into the coal car, vibrating for about three minutes without actually coming into contact with the sides of the car. They can be tailor-made to the size and shape of the hopper car. The traveling hammermill is another design developed to break up large lumps of coal before transfer to a conveyor belt. Typically used in conjunction with a standard grate-type filtering system the traveling hammermill moves over the grate, pounding large lumps until they fall through.

(b) Structures

Structures in use along waterways subject to ice must withstand static ice loads imposed by moving ice pushed ahead of vessels. Neil distinguished four principle modes of ice action on fixed piles and piers: impact of moving sheets and floes, static pressures due to expansion or contraction of the ice sheet, slow pressure from ice accumulations, and vertical movements of the ice cover due to fluctuating water levels. In practice, structures which have been damaged by ice are replaced by stronger ones, e.g., steel dolphins replace timbers, vertical sheet piling replaces concrete-capped breakwater with rounded tops, which allow wind-driven ice to spill over the breakwaters, heavier riprap is used around the bases of fixed navigational aids, and dock ladders are recessed. Also, additional protective structures are installed, such as well keyed rubble mound breakwater and ice.

The analytical estimation of ice loads on structures is a very active area of research, comprising theoretical, laboratory, and field studies around the world. A variety of papers on ice loads, based on various approaches and application may be found in the Proceedings of the Third International Symposium on Ice Problems[92]. The problem of ice accumulation of the superstructures of vessels is of particular relevence to winter navigation. Minsk[93] discusses the accumulation of ice on ocean structures, with emphasis on vessels. The factors which affect icing

severity are water source temperature, air temperature, wind speed, ship size and configuration, angle between ship course and wave heading, and ship speed. CRREL is considering future work in this area.

(c) Shore Protection

Ice in rivers and channels is a common cause of damage to protected and unprotected banks, to groins, wing dams and spur dikes, and to flood-control levees. The damage includes erosion or scour of bank material, removal or disarrangement of riprap, and breaking or shearing of piling. Most of this type of damage is attributable to moving ice, but some damage results from the first movement in the spring of channel ice which has frozen fast to the banks or the channel control structures. There has also been concern that shifting of ice and resulting pile-up may result from icebreaking operations. The extent of damage is entirely dependent on the severity of ice conditions. The heaviest damage is likely to occur on rivers where the ice cover is normally thick and the breakup is rapid. A similar degree of severity exists downstream from large ice jams which go out in a short period, releasing large amounts of broken ice. Thus even rivers which are nor normally ice covered are subject to this ice problem if floating ice comes from upstream portions of the basin. Flood-control levees are affected when moving ice accompanies high stages, such as in the case of ice jams. In terms of frequency of occurrence, ice scour and erosion is essentially an annual event, occurring at the time of ice breakup and runout. However, light ice years in southerly areas produce little or no damage, and highly variable weather conditions can cause mid-winter breakup and refreezing, so that several episodes of ice scour and erosion may occur in a single year.

The increased maintenance requirements which result from this ice problem are basically repairs to damaged areas and facilities. In the case of extensive damage to channel control structures, maintenance in the form of additional channel dredging is required to restore or maintain adequate navigation depths until the repair of channel control structures is complete. Draft reductions or delays to navigation are temporarily caused by inadequate navigation depths.

Aside from the basic repair of damaged areas, and the increased dredging requirements mentioned above, the techniques used to combat ice damage to river banks, revetments, channel control structures, and levees involve the following: use of larger riprap sizes and otherwise would be required; redesign of control structures to insure streamlining of cross-overs and to provide greater structure mass; the gradual replacement of wood pile structures with rock structures; and the regulation of flows during ice runout by upstream reservoirs. All of these techniques are viewed by district-level personnel as being only partially successful.

Longitudinal ice booms, designed to enhance the formation and maintenance of stable ice cover along channel banks, are considered valuable in channels where the flow velocity is close to the critical speed for ice formation.

A related problem of shore protection involves the particular difficulties presented by ice during oil spills. The probability of serious oil spills in the winter due to collision and grounding, may be reduced with *decreased traffic level*, improvement of navigational aids, and the presence of a clearly defined channel in the ice cover. Ongoing Coast Guard research on methods of handling oil spills in ice conditions is aimed at developing means to:

1. detect oil spills under the ice.

2. contain the spill, that is, prevent it from spreading under the ice.

3. remove the spill from under the ice.

4. dispose of the recovered oil in an environmentally sound manner.

(d) Island
    Transportation

One of the major problems associated with winter navigation in the St. Marys River is disruption of normal modes of transportation between the islands and the mainland. Because this problem resulted from extended season

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activities, an air-propelled boat-sled, capable of cross-
ing solid ice, broken ice, and open water, was constructed
to provide a reliable means of transportation during the
1973-74 winter. A number of modifications and improve-
ments, suggested by boat-sled users on Lime Island were
implemented prior to the next season. These included a
new engine and propeller, a walk-through windshield, new
passenger seats, canvas top and side curtains for passen-
ger compartment, and a sturdier engine mount.

The craft operated reasonably well during the winter
of 1974-75. It was capable of going over ice, snow,
covered ice, open water, ice filled channels, and fields
of broken ice frozen together and standing on edge,
although the ride is not smooth in the transition between
ice and water. No difficulty was experienced in entering
or leaving ice filled open water channels. Some diffi-
culty was experienced, however, in moving the boat-sled
after it had been parked on snow or ice for a sufficient
period of time for the hull to freeze to the underlying
surface.

ONGOING RESEARCH

Ongoing research in the extension of the navigation
season continues along both the regional, site-specific
approach and the general, analytical approach. The
regions of the United States where the extension of the
navigation season is of interest are the GL/SLS, the Upper
Mississippi River System, the Upper Ohio and tributaries,
and Alaska. Research programs are underway for the GL/SLS
and Upper Mississippi, and to a lesser extent, Alaska.
General research is conducted by the CRREL and the United
States Coast Guard.

The Upper Mississippi Winter Navigation Study is con-
ducted under the auspices of the Rock Island District.
The primary report released so far is the Economic Analy-
sis of Year-Round Navigation on the Upper Mississippi
River[94]. This report discusses various alternatives of
season extension varying in geographical and temporal
extent. The report is economically oriented; it attempts
to identify the season extension program with the most
promising benefit/cost ratio. The technological require-
ments and costs of implementing the various programs were

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provided by the Rock Island District based on existing technologies, and are summarized in the report. The over-all study report is due to be released shortly, and any future work will be based on the recommendations of that study, and the public reaction to them.

The GL/SLS Navigation Season Extension Demonstration Program was conducted under the auspices of the GL/SLS Winter Navigation Board, an interagency organization. The participating agencies included the Army Corps of Engineers, the Coast Guard, the SLS Development Corporation, the Maritime Administration, the Federal Energy Regulation Commission, the Great Lakes Basin Commission, the National Oceanic and Atmospheric Administration, the Fish and Wildlife Service, and the Environmental Protection Agency. This long list reflects the broad scope of the demonstration program: this report is concerned only with developments directly pertinent to navigation.

The Coast Guard has installed a chain of Loran C stations along the St. Marys River and is testing sophisticated ship board receivers known as the P.I.L.O.T. system. This system provides position information with 25 feet in the most critical reaches. Handheld receivers are also in development. These systems are described in more detail in the text under "Navigation Aids." The newest Coast Guard icebreakers going into service on the GL/SLS are equipped with polymer hull coatings and air bubbler systems which reduce resistance to motion in ice.

Ongoing projects under the auspices of the SLS Development Commission include a study of handing dams along the Seaway, hydraulic modeling of certain problem reaches to assist in the design of improved ice control systems, and the identification of the best alternative off a precise all-weather electronic navigation system.

The Alaska State Department of Transportation is sponsoring a study of Western and Arctic Alaska Transportation and a study of ferry service for the Yukon River. Both studies are being conducted by Louis Berger & Associates, Inc. Marine and inland water transportation in these

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areas must be concerned with nearly all aspects of navigation during winter conditions. In addition to the technological problems associated with dredging, river training, extension of the coastal port season, and the maintenance of navigational aids in severe winter conditions, these studies must consider problems of transshipment between marine vessels, land vehicles, and inland vessels and the appropriate public policy with respect to guarantees of the opening and closing dates of navigation.

The primary Coast Guard general research priority in the area of the extension of the navigation season is icebreaking. In addition to the innovations incorporated into GL/SLS icebreakers, the Coast Guard is working with ACVs as icebreakers. These vehicles have been found in tests to be excellent at breaking ice, but they cannot move ice away from the channel, and must depend on a favorable current. A concept which has been tested successfully is the installation of an air cushion generator on a barge, which is pushed by a buoy tender. This concept combines the effectiveness of the air cushion at breaking ice with the ability of the buoy tenders, which are now used alone as icebreakers, is considerably enhanced. A potential future application of the ACV's is icebreaking in shallow areas near riverbanks, groins, and dikes. The ACV's would break up the ice as it forms in the shallow areas and the broken ice would be carried downstream. Ice would not then be able to form in the channel. ACV's draw no water, and in fact operate on land as well as water, enabling them to break ice in areas inaccessible to conventional vessels.

The Coast Guard is also involved in the tracking of icebergs, which is particularly relevent to shipping traffic bound for the Arctic regions of Alaska. A project in the testing stage involves the placing of transmitters on icebergs which will allow the icebergs to be tracked by satellite, relieving the load on reconnaissance aircraft. A SLAR system with computer enhanced imagery is being developed in order to enable aircraft to locate icebergs, which appear on conventional radar indistinguishable from fog. The Coast Guard also sponsors analytical research into the deterioration of icebergs in order to develop a model which will enable the Coast Guard to identify the point in time at which an iceberg no longer presents a hazard to navigation.

A vessel routing system for the North Slope of Alaska similar to the ice formation system in use on the GL/SLS is under consideration.

An ongoing area of interest to the Coast Guard are the special problems presented by ice to the recovery of oil spills. Existing technologies were designed for use in open water, and new concepts are needed for use in the presence of an ice cover. There are four problems to be solved:

1. detection of oil spills under an ice cover.

2. containment of the spill.

3. removal of the spill.

4. environmentally sound disposal of the recovered oil.

The Coast Guard has recently supported original research into hypothermia and its treatment.

CRREL is a leading research institution involved in all aspects of ice engineering, including the extension of the navigation season. CRREL staff feel that the problem of operating locks in ice conditions has largely been solved, although ice adhering to the bottom of barges and hitting gate sills must still be dealt with on the river. Their major concern now is ice in channels, and most ongoing research is related to problems encountered in the connecting channels of the GL/SLS. CRREL is currently preparing a proposal for a comprehensive research program for river ice management.

The use of longitudinal bubblers at bends to increase the mixing of warmer bottom layers of water in order to weaken surface ice and the use of ice control structures, like booms, are being investigated.

Laboratory work is thought to be a bit behind field measurements, and so CRREL is trying to catch up through the use of their excellent new experimental facilities. Laboratory work in the past has been largely performed

with plastic "ice;" each research center has its own favorite polymer. In an attempt to make force measurements on modeled ice conditions more consistent with field measurements, other model materials such as fresh water ice, salt water ice, wax-based materials, and plaster-of-paris based compounds are currently being tested. Each material has advantages and disadvantages and the choice of a model ice material depends primarily upon its ability to model those ice properties most significant to the problem being studied. A Committee of Experts has been recently formed by Major General Harris to review and evaluate physical models of the GL/SLS prepared by Arctec and Acres.

CRREL's three new cold rooms contain a large basin which can be used to model specific sites, a double-bottom flume for modeling stream flows, and a towing basin for evaluating vessel performance. These rooms can be chilled to -10 degrees F (-20 degrees F in the flume), producing natural ice. Urea is added to the water in order to weaken the ice, so that certain scale effects may be taken into account.

CRREL has instrumented piles in the GL/SLS in order to make regular field measurements of ice forms. The measurement techniques for the field are said to require further refinement.

CRREL will shortly be releasing a draft Engineer Manual summarizing the state-of-the-art in ice engineering.

IX - RECOMMENDATIONS FOR FURTHER INVESTIGATION

As a result of the investigations undertaken to evaluate the state-of-the-art in waterway science and engineering, numerous topics were identified as requiring further research. This section presents suggested areas in which future research should be directed. Suggestions presented are derived from the recommendations of studies on the various topics and recommendations of experts in the various fields. To accomplish the latter, a workshop was conducted by the National Waterways Study on July 12, 1980 in Vicksburg, Mississippi. The workshop was attended by the leading experts of the Corps of Engineers in each area investigated. In addition to recommendations, a ranking of research priorities was also developed in the workshop. Accordingly, suggestions for future research are ranked for implementation in the short term, intermediate term or long term future.

Suggestions for further research on the topic "Technology for the Extension of the Navigation Season" were derived from available studies and from a meeting with experts in the field from the Corps' Cold Regions Research and Engineering Lab (CRREL).

NAVIGATION STRUCTURES

The following topics are recommended as directions in which future research should be focused:

For short term implementation:

While model tests are used extensively to develop lock filling and emptying system designs, prototype data is rarely collected to compare the model design and the actual performance. A program of prototype data collection should be developed in order to help improve future designs.

The use of savings basins (thrift basins) may soon

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find application on some United States waterways. While technology required to construct savings basins is available from European experience, specific designs will have to be developed for United States lock sizes.

Research is needed to develop improved (for increased safety and capacity) tow haulage equipment designs. These would potentially have wide spread application.

Research concerning the effect of tow size, towboat horsepower, gate sill height, etc., on lockage time and safety is proposed at Waterways Experiment Station for when funds to construct an adequate test facility are approved. Work could also include investigating the effect of submergence on filling and emptying times.

The effect or hydropower generating facilities, installed at low head dams, on navigation conditions should be researched and documented, especially with regard to sediment movement and surges. Work is being planned in this area both at Waterways experiment Station and at the division level (ORD). For fiscal year 1981, several work units have been proposed by the Waterways experiment Station of the United States Army Corps of Engineers that will address problems associated with lock/dam/hydropower releases on navigation. This could become an increasingly important area of research in the event of continued small hydro development.

Performance Monitoring System data is now collected for most locks, although, by regulation it is to be collected at all United States locks. A program designed to evaluate PMS data could identify areas of lock improvement. Such a program should be developed. In addition, a sampling plan for gathering PMS data rather than 100% collection of information is being considered by the Corps and should be pursued further. The development of a program could at the same time reduce the amount of data to be gathered and reduce the current backlog for data input to the central library from certain districts.

For intermediate term implementation:

In low and medium lift ranges, the most important topics for further research would appear to be in the area of improvement of lock approach designs. Although approach time constitutes a considerable portion of total lockage time, the knowledge of associated phenomena is lacking basic generalization. Further studies should include optimization of distances between waiting area and lock gates, type and location of mooring facilities, approach channel depth and width, required towboat power for safe entry and vessel passing measures to decrease cross-currents, optimization of approach/exit and entry times, optimization of size and spacing of guard wall ports, and so forth.

High lift locks present numerous and complex problems. Further research in high lift lock design, including types of filling systems, energy dissipation devices, and type of structure should be conducted.

In order to increase safety during lockages and accelerate the speed of entry, designs for guiding devices, such as traveling mooring bitts and impact barriers which would be appropriate for typical tows operated on United States waterways should be developed. Considering the potential dangers involved with encouraging operation (entry and exit) at higher speeds, it may be well worth while developing positive breaking devices. Both generalized and specific work should be undertaken.

Additional research is needed to investigate the hydraulics of end filling systems, as they are likely to continue to be economically viable alternatives for very low lift locks in intracoastal areas along the Gulf Coast.

Valve designs to eliminate cavitation at high lift locks are being developed; however, additional research and documenation is needed.

Additional work should be performed to develop concrete (and other materials) with improved resistance to erosion from hydraulic forces.

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A program should be developed to set up performance standards for locks. Once these standards are defined they will aid in the evaluation of existing lock performance. Along these lines, it may be desirable to revive a program of continuing and periodic evaluation of structures in order to facilitate the exchange of information between designers and operators.

Methods to reduce the dynamic forces on miter gates during filling and emptying should be developed.

Further research should be performed to further reduce dependence on physical modeling of hydraulic phenomena. Continued research on the powering and maneuverability of tows could lead to improved designs for approaches, entries, and general layouts. In particular, the relationship between approach and entry speeds and required clearances should be established for United States tows in order to improve the usage of lock facilities.

Research should be performed to identify waterway segments where the capacity of the existing locks can be increased by deepening channel depths. The clearance over the sills of existing locks and problems associated with channel deepening would have to be analyzed.

Research is required to develop bow thrusters for use in transiting locks. Work is also required to evaluate the potential effect of bow thrusters on locking speed and capacity.

METHODS OF INCREASING THE CAPACITY OF EXISTING LOCKS

In light of the fact that most of the measures discussed herein have only recently been given serious consideration, a great deal of potential exists to further develop nearly all of the measures.

For those measures which are currently incorporated as part of modern lock designs, methods should be developed to allow existing locks to be retrofitted accordingly.

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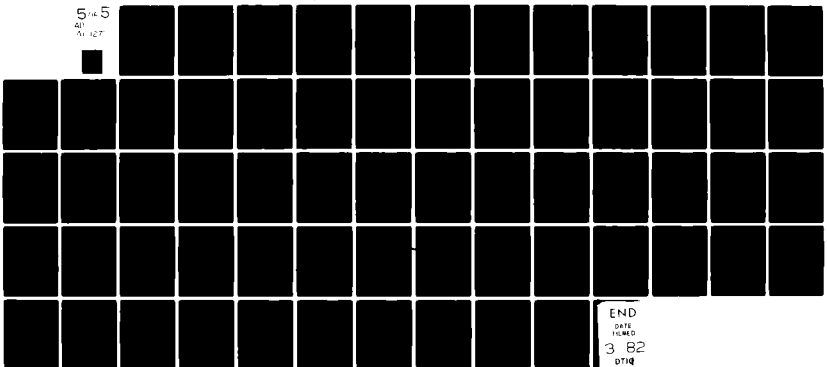
For those measures which are routinely investigated
for use at high traffic levels, generalized relationships
and costs should be developed which will allow the evalua-
tion of the effectiveness of the measure under site condi-
tions. In this way, the potential for improved capacity
could be established, for planning purposes, to defer new
lock construction.

For the remaining measures, those which have never
been applied, additional work should be performed in order
to establish which of the measures are the most feasible
and the most beneficial. Additional work could then be
concentrated on developing those measures which are the
most promising. The complicated institutional problems
associated with those measure which would require improved
industry performance should also be given consideration.

Research concerning the effect of towsize on lockage
time and the effect of towboat horsepower on safety, lock-
age time, sill heights, etc., is proposed at Waterways
Experiment Station for when adequate funding for test
facilities is approved.

CHANNEL DESIGN STANDARDS

The following topics are recommended as directions in
which future research should be focused.

For short term implementation:

The problems of solving the simultaneous partial
differential equations describing fluid flows is being
approached numerically using digital computers and sophis-
ticated techniques like finite differences and finite
elements. Numerical solutions are also hard to general-
ize. While numerical modeling is not necessarily inexpen-
sive, it can be relatively inexpensive compared to a phys-
ical model solution if it can provide an accurate answer.
Numerical modeling still has limitations and is still in
the development stage. It is expected, however, that an
increasing amount of research will be performed numerical-
ly in the future. A specific example of this type of re-
search is the effort currently underway at Waterways

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Experiment Station to develop mathematical models of tows negotiating bends. This model will be calibrated using Glover's experimental data.

The phenomena which cause tows to deviate from the desired path are also objects of research. The effects of wind, currents, alternative steering systems, and most important, human factors, all affect required channel width, and are under study using various mathematical approaches, including simulations.

The requirements for fleeting area should be formulated, including appropriate distance between main navigable channel and mooring facilities, to provide for safety and sufficient room for tow handling operation.

For intermediate term implementation:

Economics is another important area of continuing study. An understanding of tradeoffs between transit time, fuel consumption, and channel dimensions is necessary for cost-effective design of waterways. Equally important is the analysis of the economies of scale of tow size versus increasing levels of restriction. This sort of study will help identify the degree of constraint which tow operators will accept before switching to smaller and more expensive tows. Design channel dimensions are also related to the cost of maintaining a waterway. Bank erosion and sediment deposition can be affected by the size of the channel.

For long term implementation:

Two possible directions for future advances in tow maneuverability are more powerful towboats and auxiliary steering systems. The development and use of towboats with higher horsepower-to-tonnage ratios would imply greater maneuverability for tows, and thus smaller clearance and bend radius requirements. The trend toward more powerful towboats has been evident in the last decade. The effect has been that larger tows are now operating safely in the same channels where they would not have

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ventured previously. In effect, design standards have
been reduced by the enhanced controllability. Increasing
energy costs, however, work against higher powered tows,
as their fuel consumption per ton of cargo is higher.
Whether the trend toward increasing horsepower per ton
will continue is thus problematic.

Auxiliary steering systems are already in occasional
use along American waterways. Typically, they consist of
a small steerable propulsion unit placed at the head of
the tow and controlled remotely by the pilot. These
steering systems can dramatically reduce the width of the
maneuvering lane of tows both in straight reaches and
bendways as sudden yawing due to bank suction, current or
wind (to which light tows are particularly susceptible)
can be controlled.

RIVER TRAINING TECHNOLOGY

The following topics are recommended as directions in
which future research should be focused.

For short term implementation:

It would appear that the most needed direction of re-
search is to develop a set of design criteria for river
training structures and channel stablilization works. The
research should strive to produce criteria for dike
height, length, and spacing which would be correlated with
hydrological and morphological features of a river or
river segment. Information should also be included on the
expected effects of specific structures and their costs.

While the complexity of this task is well understood,
it is believed that the compilation of known design cri-
teria into an engineering manual would be most useful to
field operations. An engineering manual would allow pre-
liminary planning to be conducted with less use of costly
physical models. The screening of alternatives for
further study would be possible.

There is a tremendous amount of data available in the
prototypes which can be used to verify the effectiveness

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of analytical design methods. It should be collected and evaluated (such work is being performed for the Lower Mississippi and an intermediate report is due from LMVD in September evaluating this data).

It is strongly recommended that specific responsibility be assigned to the task of collecting and evaluating prototype data. A considerable amount of planning would be required to develop the objectives and level of detail of such a program. It may be more appropriate to analyze existing historical data than to devel op a program of data collection. A comprehensive program of data collection and evaluation should be set up which will provide a uniform homogeneous system nationwide. Emphasis should be placed on making more sense of what is known, but on a systemwide and nationwide basis.

For intermediate term implementation:

It is recognized that although the relationship between dredging and training is highly site specific, there is potential for developing a program to evaluate the relationship. Possible approaches include the determination of costs required in river training to reduce dredging requirements and the fringe benefits associated with reducing navigation delays.

For long term implementation:

It is recommended that more emphasis be placed on high flows in dike design. Increased emphasis is needed on evaluating bed load movements and developing methods to control sedimentation over the entire river morphology.

As total sediment load is being reduced in most waterways because of increasing control from upstream reservoirs, it is recommended that a basin wide approach for sediment analysis be adopted. This should include an assessment of land use within the basin and a forecasting of river response to impacts imposed by changes within the basin.

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It is further recommended that mathematical hydraulic models should be emphasized in future research. Such models can be useful to supplement and in some cases substitute for physical models. The use of empirical coefficients for these models can be recommended during the first stages of mathematical model development. It is envisioned that the empirical coefficients may gradually be replaced by theoretical equations as progress is advanced in the field of study.

Currently, as well as in the future, the combination of prototype tests, mathematical models, and physical models will be the most comprehensive way to justify training programs. The most important and least known aspect of river training is to predict the interrelation between river training and dredging requirements. Depending on river hydrologic and morphological characteristics, river training may have little effect or may completely eliminate dredging requirements. This has been proven by several examples, notably the Missouri River which has eliminated dredging and by reaches of the Mississippi River where dredging volumes have increased after river training structures were built.

DREDGING TECHNOLOGY

The following topics are recommended as directions in which future research should be focused.

For short term implementation:

1. All components of the dredging cycle should be studied to improve their efficiency. This would include an evaluation of existing equipment versus existing requirements.

2. Increased emphasis should be given to the development of the mechanical and technical components of dredging systems. Automation and computerization should be considered for a larger part of the dredging process, such as positioning of the plant, monitoring of slurry density and speed movement and rate of swing in the path of the cut.

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3. In light of the continuing energy crisis, the energy-effectiveness of dredging operations should be improved by adopting waste heat recovery measures and installing modern power plant equipment.

4. Increased emphasis should be given to improving the management of dredging operations in order to decrease unproductive downtime and the time for movement between sites.

5. Basic dredging techniques necessary for productive uses of dredged material should be developed and applied, including activities such as processing, dewatering, classifying, densification and separation of materials.

For intermediate to long term implementation:

1. Applied research efforts should be integrated and coordinated with a view towards effecting a purposeful program of dredging equipment development and improvement, with due consideration of present and anticipated needs.

2. Investigation of laminar pipeline flow and pumping with high solids concentrations.

3. The potential for increased usage of mechanical dredges, such as the endless chain bucket dredge and the fully automated single bucket dredge, should be investigated.

4. Effort should be made to develop new dredging plant concepts to provide effective solutions to the more difficult dredging problems associated with waterway maintenance.

TECHNOLOGY FOR THE
 EXTENSION OF THE
 NAVIGATION SEASON

The following topics are recommended as directions in which future research should be focused.

For short term implementation:

     1.   model testing of air curtains (currently underway).

     2.   icebreaker design for rivers; this subject is recommended for intermediate-term study as well.

     3.   field testing of ACV icebreakers.

     4.   ice forecasting; this is considered more promising for the GL/SLS and Upper Mississippi than the Ohio.

     5.   traffic management and information systems; these systems are primarily for use on the GL/SLS; they stress the advantage of real time information over forecasts.

     6.   ice effects on shorelines, docks, piers, and other structures; this broad and important area is recommended for intermediate and long term study as well. Calibration models and prototype measurements of ice loads are considered the best approaches for the short term.

New technologies which are considered feasible for incorpration into projects in the short term are:

     1.   lock wall heating elements, especially for locks being rehabilitated.

     2.   air curtains at lock entrances.

     3.   ice control by booms and other structures.

     4.   coating for lock walls and gates.

     5.   protection for floating mooring bitts.

For intermediate term implementation:

     1.   icebreaker design for rivers.

     2.   ice forecasting.

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3. the conflict between hydropower production and ice control for navigation.

4. all means of displacing brash ice from navigation channels.

5. the build-up of ice under barges.

6. the build-up of ice on vessel superstructures.

7. electronic navigation systems.

8. winterized aids to navigation.

9. speed, power, and resistance in ice fields, model studies are considered a promising direction

10. ice control for lock chambers.

11. temporarily halting navigation, power production, or both while ice forms or breaks up, or during particularly sensitive environmental periods.

12. whether improvements in water quality are responsible for more severe ice conditions.

Electronic navigation systems and winterized aids to navigation are expected to be incorporated into projects.

According to Ashton's "River Ice", additional study should be performed on the mechanism of the initial formation of frazil ice, which is not well understood. It is recommended that a systematic base of river characteristics and ice jam occurrence be collected in order to provide a basis on which to test experimental findings or theoretical conjecture on the potential of specific river sites for the initiation of ice jams. The development of a useful index of jamming potential as a function of river characteristics would be useful in determining the smallest opening in an ice retention structure that would allow vessel passage without allowing significant ice passage; predicting where an accumulating ice cover will initiate, and assessing desirable bridge spans such that they do not act as jam initiators.

X - CONCLUSIONS

Waterway development and operation encompasses a variety of subjects related to industrial technology and to the natural sciences. Among these are: the design of hydraulic structures and heavy construction works, river and coastal hydrology and morphology, operational research and the like. Waterway structure and maintenance belongs to a traditional infrastructure and as a result it is difficult to anticipate any revolutionary type of breakthrough in current technology Instead, modernization of existing installations, adjustment of technology to changing socioeconomic requirements and a better understanding of physical and operational processes are to be expected.

In observing the present stage of waterway science and technology, one may note that the efforts in this field are generally substantial and involve all major directions of waterway constriction and maintenance. However, in our opinion there is some malproportion in investigations conducted by the United States research institutions. More effort is devoted to project type, site specific studies and initial data collection than to analysis and generalization of the resultant information. Consequentially, there is a lack of planning technique, especially at the prefeasibility level of evaluation. Often an all new cycle of research is conducted for similar projects without full utilization of findings gathered for previous and similar projects.

Of course, we realize that the nature of the waterway environment, especially morphological factors, makes generalization very difficult. Nevertheless, the present state-of-the-art in related sciences, as well as the vast amount of accumulated information, warrants, in our opinion, more attention to the basic type of research. This would be especially helpful for the screening of alternatives, which in turn can provide a more comprehensive evaluation of the engineering and economic problems, while simultaneously reducing planning and design costs.

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The following sub-section presents a brief summary of findings and observations which result from the review of waterway science and technology presented in this report.

NAVIGATION STRUCTURES

Locks may be classified by lift as follows:

- very low lift   under 5 feet

- low lift   from 5 to 30 feet

- intermediate lift   from 30 to 50 feet

- high lifts   over 50 feet

The above classification reflects, to a large extent, the complexity of design, and the type of construction involved. For lifts of under 5 feet, locks with earth embankment walls may suffice. For lifts over 50 feet, the only choice is concrete construction with a hydraulically well designed filling and emptying system.

Simplified less costly types of locks can be designed, but in all cases filling and emptying times will be increased, safety will be lower, and the capacity will be lower than the capacity of a conventional design concrete lock that can be filled or emptied more rapidly.

Because of foundation and stability problems with gravel filled cells, the 13.4 foot lift at Dam 53 is probably about the maximum that should be considered for a lock that is planned for 10 to 20 years use. The sheet pile cell lock is suitable for low lifts on secondary tributary waterways where tows or vessels are not large (5,000 to 10,000 tons); where traffic (existing and potential) is light; and where interruption to traffic would not constitute a major disaster.

For concrete locks, foundation conditions at a specific site, where the lift is over 10 feet, may determine whether the lock will be designed with: gravity walls supported on soil; gravity walls supported on friction

piles; gravity walls supported on end bearing piles; gravity walls on rock; drydock type structure supported on soil; or drydock type structure support on piles.

In the future, very low lift locks will probably be built similar to the Calcasieu Lock, or the Pearl River Lock in sizes up to 600'x110'. For sizes larger than this for heavier tows, and where traffic density is greater, concrete construction will probably be required.

A number of studies have been performed which investigated the feasibility of several types of locks and lifts solely for recreational craft. The technology required to construct a recreational lock or mechanical lift is available.

Hydraulic model studies, and verification of the model studies with full scale prototype tests, examining channel levels, river currents and channel depth, are an absolute necessity if costly mistakes in lock siting are to be avoided. In selecting a location for a lock and dam within a certain reach, there are general guidelines which have been formulated, based on practical experience and the results of research.

On streams where sediment movement is not a major factor, the lock and gated spillway section of the dam should usually be located on the concave side of a very flat bendway or on the side of a naturally straight reach where the channel is the deepest and the most stable. The lock should only be located on the convex side of the river if all other options are investigated and found to be inferior.

Where it is necessary for a canalized portion of a waterway to descend an escarpment or a preciptious drop, the descent can be made with flight locks, with several low lift locks separated by short intermediate pools or with a single high lift lock. No general conclusion or rules to govern such a selection can be developed because, terrain, capacity and other features will differ from site to site. Lifts very much in excess of 100 feet experience

difficulties in design and operation as cavitation at the valves and other hydraulic and structural problems become more critical.

At locations where it becomes necessary to build two locks, based on the results of model studies, two layouts have been developed which when adopted at future sites should provide safer and more efficient movement of traffic through the locks. The first layout uses adjacent locks and the second uses separated locks.

When locks are to be placed adjacent to each other, it is preferable to separate them with relatively long guide walls providing enough space to permit simultaneous movement of vessels into and out of both locks. Alternately, the two locks should be separated by 1.5 to 3.0 lock widths with a section of spillway between them so that all flow upstream from the locks is not blocked.

The latter arrangement (separated locks) was studied in model studies for the proposed New locks and Dam No. 26 on the Mississippi River at Alton, Illinois.

Particular attention has to be given to the layout of a lock that is being placed in a dam where hydropower is a main feature. The lock must be located so that flow to the powerhouse as well as to a spillway will not create adverse currents in the lock approaches. Under today's conditions the most likely location where a navigable dam would be feasible would be on secondary waterways or on a tributary of a fairly large stream, where the large stream experiences long periods of high stages that creates very flat backwater slopes for an appreciable distance up the tributary. Navigation dams can be considered as replacement structures for existing navigable dams.

Rational selections of a maximum size lock, at the present, should be governed by the maximum size tows that could use the waterway (two-way traffic) without excessive channel improvement work; the type of towing equipment in general usage; the expected amount of traffic; economics; and the lock sizes on connecting waterways.

In the early 1960's, attempts were started to fix certain standard lock sizes to prevent a continued proliferation of sizes. The sizes recommended for commercial locks are 84'x400', 84'x600', 84'x720', 84'x1200', 110'x600', 110'x800' and 110'x1200'. It is anticipated that further needs for lock sizes will continue in the 84 foot widths and 400 to 1200 foot lengths.

Research during the past 20 years has fairly well determined the characteristics and defined limitations of the four general types of filling and emptying systems. On secondary waterways with lifts in the very low to low lift range, end systems and side port systems will continue to be used. Designs for side port filling systems have been standardized so that design of these systems under normal conditions in three sizes can be developed without resorting to model studies. For intermediate and high lift locks, it will probably be necessary to use concrete locks with bottom longitudinal systems. However, designs for intermediate and high lift locks must be selected after economic comparison with side port and multiport systems, particularly for lock lengths of 600 feet or less. Thus far, there have not been enough locks built using bottom longitudinal systems to allow their design without model studies. Thus, high lift locks to be constructed in the foreseeable future will require hydraulic model testing of the filling system in order to insure adequate design.

The reverse tainter filling and emptying valve has been widely adopted in the United States for all concrete locks in the low to high lift classifications with side port, bottom lateral or bottom longitudinal systems. In future lock construction, reverse tainter valves will be used more than any other type. Exceptions to the use of the reverse tainter valve may occur with end filling systems and possibly water saving basin locks. Butterfly valves and slide valves can be used for very low lift locks and slide valves designed for head in either direction may be necessary for water saving locks.

For the foreseeable future, lock gates in the United States probably will be miter, vertical sector, submergible, tainter or overhead vertical lift types. Most future locks will have miter gates. For very high lifts

locks, submergible upstream tainter gates and overhead vertical lift gates or miter gates probably will be used. For very low lift locks, either miter gates or sector gates may be used (sector gates where head reversals are possible).

Poor approach conditions currently exist at some locks which could have been mitigated if modern, improved design techniques had been available at the time of construction. For many of these locks, improvements may be possible by modifying the existing approaches. Possible modifications include:

1. realignment of the approach channels.

2. realignment or modification of the auxiliary walls.

3. installation of river training structures.

4. installation of submerged dikes.

5. installation of guard cells.

6. extension of the auxiliary lock walls.

7. installation of wing dikes.

8. provision of mooring cells.

9. elimination of obstructions.

10. elimination of debris.

11. reducing the effect of filling and emptying on powerhouse operations.

The above approach channel improvements might bring some existing poor approach channels in line with modern standards. Ideal approach conditions would permit fully loaded tows to become aligned for approach into the lock some distance upstream of the lock and then drive or drift toward the guide or guard wall with little or no maneuvering or engine reversal required.

One of the most important advances in providing safety to tows and to tow personnel is the use of hydraulic models to examine the approach conditions at a specific site. This valuable tool enables designers to determine the strength and direction of currents in lock approaches and to develop layouts and approach channels that generally eliminate dangerous crosscurrents that would cause a tow to founder on the dam and sink.

The increasing frequency of accidents that damage lock gates is focusing attention on impact barriers and satisfactory designs will be developed. The use of impact barriers will undoubtedly increase the initial cost of some locks, especially if lengthening the lock chamber is necessary.

Towing mooring bitts, or towing kevils, have been studied and could increase the safety and speed of lock transits but have some disadvantages which require further study.

Designs of a proper depth over sill should be based on the following factors: (a) vessel entry speed and consequently lock capacity, (b) the possibility of lock usage under ice conditions, (c) improved safety and (d) the possibility of long term changes in water levels due to water usage, morphological shifts or other changes which may change the allowable tow draft.

To date, no research has been performed in the United States to evaluate the effect of reduced clearances on lock service time and navigation safety. Thus, no precise assessment can be made of the effect of clearance on lock capacity based on American research with tow sizes and lock sizes in use in the United States. The design recommendations of ETL 1110-2-223 of the Army Corps of Engineers[95] are based on tests performed in Europe where it was found that efficient entry times were obtained when the sill depth was 1.8 to 2.0 times the vessel draft.

On most filling systems, especially side port systems, proper design and functioning of a lock's filling system is contingent on the depth in the lock chamber. This

required lock chamber depth is almost always greater than the available channel depth by a substantial amount. Thus, the draft to which tows can be loaded is fixed by channel depth and since the lock chamber depth has to be substantially greater than the vessel draft, there remains only the question of the proper elevation for the lock sills. By increasing the depth over sill for low and intermediate lift locks, additional crosssectional space for improved hydraulic performance can be obtained at no increase in lock cost, which tow operators cannot encroach upon.

Studies have shown that the use of water saving basins (thrift basins) should be considered in areas where adequate water may not be available to allow regular cycling of a)ck.

In general, whenever lifts have exceeded about 65 feet, Europeans have found shiplifts more competitive than high lift locks for vessels with a cargo capacity of 1350-1500 tons. According to studies made in the Union of Soviet Socialist Republics, the installation of shiplifts becomes feasible for vessels designed for a cargo carrying capacity of 5000 tons, beginning with lifts of 165 to 200 feet. This limit is evidently in the neighborhood of 130 feet with 2000-3000 ton vessels.

Currently, no shiplifts have been constructed with a length exceeding 330 feet, so that barge tows must break before using them. Due to the very small size of the shiplifts, which would only be capable of accommodating one or two United States barges, it is very unlikely that the use of shiplifts instead of locks could be justified in the United States. However, the widespread use of shiplift structures and their history of reliable operation attests to the soundness of the technology.

During recent years, heavy construction has benefited enormously from the technological progress and widespread use of prestressing techniques within the construction industry. This resulted in a variety of uses for prestressing rods and tendons being developed as earth tie-backs, as rock anchors in excavation support systems, as

members resisting lateral and uplift forces, for solidi-
fying the subsurface soil strata and for stabilizing fis-
sured rock formations. This was possible due to the
development of new anchoring devices, tensioning equip-
ment, grout and grouting procedures.

Economies may be achieved by precasting various ele-
ments of a lock structure and/or by precasting entire seg-
ments of locks and assembling them by using post
tensioning and prestressing methods. An example of pre-
fabrication is the proposed new Inner Harbor Navigation
Canal Ship Lock. Siting restrictions on the new lock,
which must be rebuilt in the same location as the existing
lock, and the necessity to minimize closure of the canal
to navigation resulted in the decision to utilize offsite
constructed floating lock elements in order to minimize
construction time.

As a result of technological improvements in the
design of locks and dams over the past several decades,
navigation safety has improved, service times have
decreased, maintenance requirements have decreased and
operation has improved. Savings in these areas resulting
from the improvements are believed to have offset the
increased construction costs which in many cases have
resulted.

It is likely that continued investigation to improve
the safety, and other aspects, of lock facilities will
result in additional improvements which will add to the
cost of the lock facility. However, as additional work is
performed to generalize design for gates, valves, and
filling systems, the engineering cost to develop or adapt
these designs on a site specific basis will be reduced.
For example, the design for the side port filling system
has been developed to the point where model tests are not
required to design these systems for normal conditions and
for the applicable range of lifts for three sizes of
locks.

The cost of locks and dams may also be reduced as new
heavy construction techniques discussed are applied in the
construction of lock facilities or as additional tech-
niques are developed. The use of some new techniques may

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actually increase costs, as it may be possible to develop new designs which were considered infeasible, using conventional construction techniques. (The offsite prefabrication construction of lock segments to be floated into place, for example).

METHODS OF INCREASING THE CAPACITY OF EXISTING LOCKS

Methods which have been proposed to increase the capacity of locks logically fall into two categories of tehnological feasibility, those measures which have been and are currently used, and those which may find application after additonal research is conducted.

Measures which are currently used to increase the capacity of locks include:

- improvements in lock operating equipment.

- improving lock approaches.

- *provision of mooring cells.*

- installation of wind deflectors.

- installation of tow haulage equipment.

- installation of floating mooring bitts.

- greater use of the auxiliary chamber.

- invoking an N-up/N-down policy.

- use of switchboats.

- guide wall extension.

- invoking a Ready-to-Serve policy.

Measures which may find application in increasing the capacity of locks include:

1. centralization and automation of controls.

2.   provision of separate facilities for recreational craft.

3.   installation of impact barriers.

4.   installation of replaceable fenders, energy absorbers and/or rolling fenders.

5.   provision of waiting areas near lock gates.

6.   establishment of more responsive and flexible scheduling procedures.

7.   water traffic regulation.

8.   industry improvements such as increased tow powering, use of bow thrusters, use of a universally adaptable coupler for joining barges and others.

To date, all quantitative results of investigations to increase capacity by non-structural and minor structural means have been obtained for specific locks so that in order to identify the benefits (in terms of increased lock capacity) possible at other locks, site specific information must be obtained. The development of generalized relationships which could be used to evaluate the relative benefits and costs of these measures would be highly desirable and facilitate their investigation at other sites.

It is advisable to continue to investigate on a case by case basis locks which have abnormal filling, emptying and chambering times. In this way, the reasons for the inefficiencies can be identified so that measures to improve service times can be proposed. The implementation of measures to provide major reductions in equipment operating times will continue to provide major benefits at some sites. Likewise, minor improvements to several components could, in combination, provide major benefits.

For fiscal year 1981 three studies have been proposed by the Waterways Experiment Station of the Army Corps of Engineers to study means to minimize the effect of hydropower generation or navigation. It is likely that measures to reduce the effect of hydropower releases on tow movements in approach channels will be developed.

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Currently, active programs of mooring cell construction at existing locks are being undertaken or have been completed in a number of Corps Divisions (i.e., ORD, LMVD, SWD, NPD, NCD). The primary purpose of these cells is to improve navigation safety, as an additional benefit, however, because required safe passing clearances are reduced when one vessel is moored, there is potential to construct the mooring cells closer to the lock rather than at the existing approach points and thus reduce approach times.

Wind deflectors, radar reflectors, haulage equipment and floating mooring bitts have been successfully installed at existing locks to improve tow passage.

The so-called N-up/N-down rule is effective only if the sum of average times for a turnback exit, a turnback, and a turnback entry is much less than the time for an exchange exit and entry. When this is the case, the lock may be reversed, and a new tow can enter the chamber faster than two tows can exchange use of the lock.

Where heavy traffic conditions occur frequently, it has been demonstrated that the use of an extra towboat at the lock has been very effective in passing traffic by reducing the time required for double lockages. A reduction in the exit and clear times for both the unpowered and powered cuts of double lockage tows is possible.

An alternative to reassembling in the downstream approach is to provide an extended guide wall for reassembling (the landward guide wall or the guard wall between the main and auxiliary chamber could also be extended).

The effective capacity of a lock with extended guide walls in an approach would be about the same as employing a switchboat, as long as a N-up/N-down procedure is followed and haulage equipment is provided. In order to achieve the same capacity with guide wall extension, the last of a series of one-directional lockages should be a single lockage in order to minimize delay to the tow approaching from the opposite direction.

The Ready-to-Serve policy, if invoked at a lock, would provide the greatest benefits of any measure as all tows would be required to lock as singles.

Installation of a closed circuit television covering the lower discharge area with receivers in both the upper and lower control stands and position indicators that would depict the exact position of all the valves would provide the lock operator with a continuous view of the discharge conditions and eliminate many trips to observe the area. Alternatively, filling and operating sequences could be automatically controlled.

At locations where congestion can become acute during some periods, consideration can be given to improving the efficiency of recreational usage to avoid occasional congestion. A practice which has gained acceptance at a number of locations is to restrict recreational lockages to scheduled hours. A measure which has been given increased consideration recently is the installation of separate recreational locking facilities. This measure would effectively eliminate congestion due to recreational usage. Separate recreational facilities can be either locks or mechanical lifts. Of course, the dimensions can be significantly smaller than conventional locks to handle recreational craft either individually or in groups.

Impact barriers, to prevent vessels from striking lock gates, are coming into wide usage in Europe but have not been used in the United States except at the Soo locks and at the St. Lawrence Seaway locks.

Most European locks provide an offset waiting location close to the lock entrance. The development of a similar type of offset waiting area in the United States is hampered by a lack of general knowledge as to the maneuverability of American tows but may not be feasible.

To decrease the inefficiencies arising from a rigid scheduling procedure, it may be possible to develop a responsive and flexible scheduling algorithm to establish which chamber a tow will use, the order of turn in which the tow will be served, and the lockage procedures which the tow must adhere to.

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A computer program which was developed for use at Lock and Dam #51 on the Ohio River considers, rapidly, all the possible orders in which tows waiting in queue at the lock could be locked. The order in which tows would be selected to lock would be based on the minimization of an objective function. Unfortunately, many of the parameters to which the program was not sensitive, such as visibility, river currents, wind, crew capability and commodity types could not be developed for incorporation without a considerable amount of effort.

In many instances, lockage times are long because the tows are not operating very efficiently. In order to encourage tows to become more efficient during the lockage process, rules could be developed for maneuverability, such that arrivals at an initial point for a given lock would gain priority according to their ability to move rapidly through the lock when waiting lines exit. Information on the speed and maneuverability of the vessels would have to be relayed to the lock operator so that he could then choose the best sequence for lockage.

In a Vessel Traffic Management System, a traffic manager could have a radar screen to assess the traffic pattern. There are three possible levels of radar utilization. At the first level, the radar observer can communicate with the vessels he observes on the radar screen. At the second level, he is assisted by a limited information processing system which enables him to better plan and control traffic. At the third, most sophisticated level, a link is set up between the information processing system and the radar unit making vessel identification and continuous tracking possible and allowing the waterway capacity to be further expanded. The most up-to-date Air Traffic Control Systems are based on the principles of the third level system.

With the exception of busy maritime ports and coastal ports which serve for the transhipment of cargo to the inland fleet, it is very unlikely that a system as complex as the third level system would ever become necessary.

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Of the four systems of traffic management investigated for use in the United States, the complete traffic and waterway status alternative was found to be the most cost effective when benefits of increased productivity, reduced operating costs, increased safety, increased reliability and increased convenience were examined. The system would transmit data from each lock into a central computer system which could be accessed by a range of users. A pilot study to further examine the feasibility and effectiveness of this alternative was recommended but to date has not been undertaken.

Three areas of current technology if universally applied would have a significant effect on lock transit speeds:

  1. increased tow speeds.

  2. use of bow thrusters.

  3. use of a universally adoptable coupler for joining barges.

In the area of long term industry planning, many types of hardware changes are possible, including improved barge shapes, use of "automotive coupled units" and hybrid types of equipment. These types of improvements, along with improved industry cooperation and sharing of equipment, would not only reduce lockage times but could improve usage of chamber dimensions and reduce empty backhaul.

CHANNEL DESIGN STANDARDS

Corps design standards are based on a given set of conditions, tow size, and horsepower; private towing companies may find it economic to operate larger tows in less favorable conditions, trading off the increased difficulty of navigation for the economies of scale of larger tows.

The selection of design depth, as has been discussed before, is largely an economic decision once the physical requirements for the passage of vessels have been met. It is unlikely, however, that reductions in transit time or fuel consumption could justify the cost of constructing and maintaining a channel significantly deeper than the

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minimum requirement. In practice, tow operators load
their barges to whatever draft will allow them the
clearance which they feel is acceptable. This draft is
often 8 or 8.5 feet in a 9 foot channel, less if the
bottom is hard or the cargo is hazardous. Thus, a design
standard of one foot of clearance in inland waterways
after draft, sinkage, trim, and waves have been accounted
for is effectively maintained in the United States.

The size of design lateral clearances depends on many
factors. Local weather conditions, specifically the
occurrence and predictability of fog, wind, and currents
and the power and maneuverability of tows must be con-
sidered. Human factors are also involved, the skill and
experience of pilots and the level of stress to which they
will be subjected should also feed into the design
decision. Finally, lateral clearances are safety factors,
and the problem of defining an appropriate level of safety
is never easy to solve. The question hinges on whether
waterways are to be designed as restricted. improved, or
first class transporting arteries. The complexity of
these considerations account for the number and range of
existing clearance recommendations.

The recommendations of the Engineering Manual EM
110-2-1611, 1980, "Layout and Design for Shallow Draft
Waterways," for minimum required channel widths are very
similar to recommendations of Daggett and Shows and of
Hochstein.

With regard to increased width in bends, the only
available sources of drift angle data that are extensive
enough for wide application are the current draft Engineer
Manual and the empirical formula in the INSA report. The
detailed analysis of the experiments of De Ruiter and
Bouwmeester is available only in Dutch.

Glover's experiments dealt with extreme conditions -
tow with barely enough power to drive through the bends
and minimal depth available. The INSA report uses an
empirical formula based on typical or average conditions
at bends. A comparison of the channel widths at bends
recommended by Glover with existing channels and current
tow sizes suggests that Glover's widths are more

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generous. Even according to INSA, there are many bends which tows can negotiate only with extreme difficulty.

Many of the design rules discussed above are either crude rules-of-thumb based on experience. Relatively few result from systematic analytical and experimental research, although the trend is in that direction. Much of the research is oriented toward specific waterways, rather than a broad range of tow and channel sizes and configurations. The reason for this state of affairs is that the problems of channel dimensions cannot be investigated in isolation; hydrodynamic problems are bound up with the design of propulsion and steering systems, the effects of wind, bank erosion, human factors, and economics. Those hydrodynamic problems which can be separated out depend on so many variables, including the tow and channel dimensions, shape, and tow speed, that analytical solutions are intractable and experimental results hard to generalize. It is difficult to make valid simplifying assumptions because of the subtle and complex interactions of the tow and channel. This last topic is a major area of continuing hydrodynamic research.

Potential increases in the safety of tow operations in restricted channel conditions and reductions of the stress level of pilots are strong incentives for the enhancement of the maneuverability of tows. A by-product of the new technologies which have been developed in response to these needs is the ability of large tows to operate in smaller channels, or with less restriction in the same channels, than before. Advances in towboat technology effectively allow channel design standards to be eased.

RIVER TRAINING TECHNOLOGY

There is insufficient knowledge regarding the complicated interrelationships influencing alluvial channels and the effects river training has on these channels. The available theory do not provide quantitative answers and the state of art in river training relies, as it has for many years, largely on individual engineering experience.

Channel stability is an area of uncertainty which has profound implications for future river training efforts.

Many navigable rivers (because of training structures, channelization, and/or locks and dams) are relatively stable. Other rivers are believed to be still in a state of flux and the long term morphology of these rivers is subject to debate. Many millions of dollars have been spent nationwide on bank stabilization but there is still considerable erosion losses. Cost effective approaches are being emphasized in bank stabilization research.

Increasing emphasis is being placed on the importance of understanding the morphology of rivers and working within the "natural" guidelines dictated by the river itself. Maintaining channel sinuosity within a dominant flow regime is a concept which appears to have merit. The morphological approach attempts to understand the rivers desired alignment and to work within the parameters established by the river as opposed to extreme modifications of the river to suit human requirements.

It appears that the present concept of the design and location of river training dikes is being subjected to some modifications. Many of the dikes constructed on rivers in the past have not taken into account the streamlines of fluid flow. These structures have been placed such that streamlines are distorted thus producing excessive turbulence with unpredictable results. Present day thought proposes that structures be designed to work with the river endeavoring to maintain the streamlines. Further, the structures should, in some instances, be built in a series of steps in order to allow the channel time for an orderly adjustment.

The impact of river training of dredging requirements has been most significant on rivers which have control overflow conditions because of reservoir regulation. The Missouri and Arkansas Rivers are notable examples of this condition. River training has progressed on the Lower Mississippi River to the point that the number of dredge sites has been reduced. Although the total volume of dredging has not decreased it is believed that the lag time effect of training will produce a decrease in the future.

The cost of river training is site specific and is
dependent primarily on the availability of materials and
the distance and accessibility requirements of trans-
porting the material. Rip rap and articulated concrete
mattresses on the Lower Mississippi will be, by far, the
most used material for revetment projects.

River training can be used to provide a stable
channel. However, experience has shown that on most
waterways it is difficult to expect that river training
will completely exclude the necessity of dredging. The
Missouri River appears to be an exception to this genera-
lization. More commonly, a combination of both main-
tenance dredging and river training is necessary. The
relative proportions of these combinations are determined
by site specific hydrological and morphological factors as
well as a consideration of the cost ratio between the
methods. The cost ratio is typically influenced by such
factors as the availability of materials for river
training and the environment constraints imposed on dredge
operations.

Given the construction approach which produces a grad-
ual transition to the present river form, it is then
necessary to evaluate current and past plans of regulation
and stabilization of the total system. This is particu-
larly true for the Lower Mississippi but also applies to
other rivers as well. It is apparent that cutoffs and
tougher training structures have increased navigation
depths on the Lower Mississippi. However, there are some
indications that the river is attempting to rebalance its
regime within the confines of manmade devices of cutoffs,
dikes revetments and other structures. The stability of
the Lower Mississippi River is subject to debate and there
are varied opinions within the Corps. Alterations of the
current plans of control may be necessary in order to
assure the orderly movement of sediment through the system
and thus assure adequate navigation conditions. It is
conceivable that it will take a long period of time to
accomplish a program which will significantly improve the
present conditions and the success of such a program will
be partially dependent upon presently undeterminable river
responses.

Observations of river training outside of the United
States indicates that the Union of Soviet Socialist

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Republics has developed some generalized criteria which
are similar to the Corps approach. European revetment
projects are generally less capital intensive but main-
tenance and repair expenditures are many times higher than
the United States standards.

Research is underway to develop improved river
design criteria. It is doubtful, given present under-
standing of certain aspects of river mechanics, that it
is possible to provide design criteria which are univer-
sally applicable. However, it appears that some gener-
alizations to provide guidance for, at least, the initial
assessment and design of river training structures can be
developed and are urgently needed. A considerable amount
able bed and math modeling on a site specific basis is,
and will likely continue to be the research tool for the
final design criteria. It appears, also, that the knowledge
of all natural sciences is expanding rapidly and future
programs will require flexibility in order to incorporate
new knowledge and data as they are developed.

DREDGING TECHNOLOGY

Historically, the general dredging practice employed
in the maintenance of the nation's waterways was that
which would accomplish the task at the lowest overall
cost. Since the mid-1960's, though, other considerations
have also come to play a significant role in the evalu-
ation of a dredging project. In addition, a continuing
emphasis is being placed on the benefits which could be
derived from the many applicable productive use concepts.

Five hypothetical settings for dredging and disposal
operations have been formulated depending on specific
dredging and disposal requirements and considerations.
Based on these requirements and their severity, the
options for specific dredge plant types and discharge
loading, transport, and unloading methods become more
limited. In turn, these factors will determine the costs
of operation.

Dredged material has often been put to productive use from dredging operations of the national waterways. This material has been widely utilized at or near the dredging site for such beneficial purposes as haul road construction, dike raising, and beach creation and restoration. The improvement and formation of wildlife habitats has been a positive by-product of dredging operations, although often accidentally. Dredged material is being employed to create specific upland areas and marshes, and also small islands for bird sanctuaries. Further know-ledge is still needed in the area of dredged material use.

More rigid requirements and considerations in some of the waterways have greatly increased dredging costs. Improvements in dredge technology and in efficiency of dredge operation are the two main elements which tend to counteract increased dredging costs resulting from these requirements.

Although the existing United States dredging fleet may be considered capable of adequately performing the foreseeable dredging workload, modernization is unquestionably desirable in order to increase the overall effectiveness in accomplishing work under varying conditions. These are influenced significantly by present and anticipated disposal requirements. Also, in the case of certain difficult dredging problems associated with waterway maintenance, there is an apparent need for developing new dredging plant concepts.

Applied research and development of dredging systems has been and continues to be undertaken by the Corps of Engineers, dredging equipment manufacturers, and a few dredging contractors. The innovations associated with these developmental efforts generally are intended to improve productivity, effectiveness, and versatility of the dredges.

Areas for further research on dredging include refinements in techniques for productive use of disposal material, improved energy efficient plant design, improved management and automation of dredging operations and in general, the development of improved dredging systems and new plant concepts.

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It appears that as greater emphasis is placed on disposal requirements and considerations and more rigid criteria and controls are established, that despite technological improvements and new innovations in dredging equipment and practices, there still will be some upward acceleration of dredging costs exclusive of the effects of inflation factors.

TECHNOLOGY FOR THE
EXTENSION OF THE
NAVIGATION SEASON

Recent developments in the technology for extension of the navigation season can reduce the cost of continuing waterborne transportation in the winter, and can increase the capacity, reliability, and level of safety of winter waterway operations.

At locks, the use of air screens and diversion channels rather than personnel with pike poles to keep floating ice out of the chamber and especially out of gate recesses, reduces the operating cost of the lock and increases the lock capacity as the time spent clearing the chamber of ice is reduced. The use of a specialized ice saw or heating elements to remove the ice collar around lock walls, instead of scraping it off with a backhoe, saves time and money and reduces damage to the lock improving reliability. Polymer coating on lock walls and gates further reduce the time and expense associated with ice removal. Heating of lock machinery and the use of low temperature lubricants improves reliability, as the machinery is protected from the rigors of winter operation.

Ice booms promote the formation of a stable ice cover, through which vessels can pass without help from icebreakers, reducing cost. Safety and reliability are increased as ice jams are prevented from forming and the risks of flooding or formation of an impassible wall of ice are reduced. Improvements in the effectiveness of icebreakers such as hull coating and air screen systems which reduce drag, and the application of ACV technology reduce the cost of icebreaking, and enable the icebreaking fleet to increase the level of the availability of the channel. The development of cargo vessels which do not

require icebreaker escorts and the development of warping
and kedging systems for critical reaches reduces ice-
breaker requirements and hence cost. Vessels which can
traverse waterways impassable in the past by any means,
reduce the cost and increase the reliability of the inter-
national transportation network by providing a new link
not previously available. Bubbler systems and warm efflu-
ent can prevent ice from forming, reducing the cost of
vessel operations. Electronic aids to navigation which
replace buoys reduce the cost of maintenance of the buoys,
and provide increased safety and reliability for vessels
operations through their accuracy and ease of use in all
weather conditions. Ice forecasting, surveillance and
information system provide increased safety and relia-
bility to vessels and reduce cost, as ships can avoid any
hazards on impassable reaches, and can identify the route
presenting the thinnest ice.

Better understanding of structural design for ice
loads, allows structures to be designed with appropriate
safety risks. Cargo handling technology which expedites
vessel loading and unloading in ice conditions reduces
port time for vessels with associated cost savings.

These technological improvements in safety,
reliability, and capacity and reductions in cost make
season extension proposals more attractive. Programs
calling for additional extensions, both geographical and
seasonal which were only marginally feasible in the past
may now be acceptable, if new technologies are employed.

GLOSSARY

Accretion: Process of enlargement or growth via adherance.

Agitation Disposal: A method of dredge disposal which resuspends sediment in the channel rather than transporting the material away from the dredge site.

Approach: Travel of a tow from the approach point, or from a point on the lock guidewall clear of the lock gates in the case of a turnback approach, to a point where the bow of the tow is abreast of the lock gates and the tow is parallel to the guidewall ready to enter the lock chamber.

Approach Point: The closest point to a lock at which one tow can safely pass another tow traveling in the opposite direction. Tows may not normally proceed beyond the designated approach point of a lock without the permission of the lockmaster.

Approach Speed: Rate of movement of tow during approach.

Approach Time: Time passed by the tow in the approach as above.

Authorized Depth: Depth of channel provided for by regulation.

Authorized Dimensions: Dimensions (width, depth) of channel provided for by regulation.

Auxiliary Chamber: A chamber of a multiple-chamber lock which is usually smaller and used less than the main chamber. Auxiliary chambers are normally used to pass small tows, light boats, and recreational vessels, and to maintain navigation during periods when the main chamber is shut down.

Barge: A non-self-propelled, usually flat-bottomed vessel, used for carrying freight on inland waterways.

Beam: The width of a vessel at its widest point.

Bed Load: The sediment carried by the river which propogates along the river bed.

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Booster Pump: For pipeline dredge material transport, an auxiliary pump in addition to the dredge pump.

Block Coefficient: The ratio of the actual displacement of a vessel to the product of its length, beam, and draft.

Canal: A man-made waterway.

Canalization: Creation of a waterway by construction of locks and dams, river training works, new channels or canals, and combinations of these.

Capacity: The tonnage which can be put through a lock during a given period such as a year, under specified conditions.

CFS: Cubic feet per second, a measure of the rate of flow of water past a given point, such as a dam.

Chamber: The part of a lock enclosed by the walls, floor, sills, and gates; the part of a lock within which the water level is changed as vessels are raised or lowered. A lock may have more than one chamber, and they may be adjacent or laterally separated.

Chambering: That part of a lockage cycle starting at the end of the entry and ending when the exit gates are fully recessed, or when the bow of the exiting vessel crosses the lock sill, whichever is earlier. Chambering includes closing the entry gates, filling or emptying the lock chamber, and opening the exit gates.

Chambering Time: The time it takes to close the entry gates, fill or empty the chamber and open the exit gates.

Channel Maintenance: Dredging, lighting and other operations which assure or maintain the navigability of a channel.

Channel Reliability: Refers to the percent of time a channel maintains a specific dimension.

Channelized River: A river which is deepened in parts in order to provide a navigable waterway.

Clamshell Dredge: Dredge equipment which utilizes two bucket edges, like opposing shovels, to lift dredge material.

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Confined Disposal: For dredged material, disposal in an area enclosed by dikes or levees.

Constraining Lock: The lock on a particular waterway or channel having the least capacity.

Controlling Depth: The minimum depth of a channel, which determines the maximum draft of the vessels utilizing the waterway.

Cut: A segment of a tow which is put through a lock separately from other segments of the tow.

Cutterhead Dredge: A dredge which utilizes a revolving head to bite and loosen bottom materials.

Dedicated Tow: A tow composed of a towboat and barges which always stay together and are operated as a unit.

Delay Function: An equation defining the mathematical relationship between the traffic level at a point, such as a lock, and the resultant delay period.

Delay Time: The time elapsed from the arrival of a vessel at a lock to the start of its approach to a lock chamber; the time spent in queue awaiting lockage.

Demand: In economics, the amount of a particular commodity people are willing to buy at specified prices.

Design Discharge: For hydraulic structures, the maximum possible flow which can be released by a given structure, like a dam, for channel maincenance the lowest discharge at which authorized depth should be provided.

Dike: An embankment which is constructed to control or redirect flow in a channel.

Dipper Dredge: Utilizes a stationary single shovel as opposed to a clamshell dredge.

Double Lockage: The type of lockage performed when a tow passed through a lock chamber in two segments or "cuts."

Downtime: The time a lock is not operative.

Dragline Dredge: A dredging tool utilizing a single bucket pulled over dredge material toward a stationary crane.

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Dredging: The process of excavating or cleaning out a channel for the purpose of providing a certain depth.

Draft: The depth of water displaced by a vessel.

Dustpan Dredge: A type of dredge which removes material with water jets, then transports the material through the pump and discharge line via suction.

Entry: That part of a lockage cycle starting at the end of the approach and ending when the tow or cut is secured within the chamber and the gates are clear, or when the closing of the gates has been initiated, whichever is earlier.

Entry Time: The time taken from the end of approach (when the bow is over the sill) until the tow is secured in the chamber.

Exchange Approach: The type of approach executed when the vessel inbound to the chamber passes a vessel outbound from the chamber.

Exchange Exit: The type of exit executed when the vessel outbound from the chamber passes a vessel inbound to the chamber.

Exit: That part of a lockage cycle starting at the end of chambering and ending when the lock has completed service a vessel or cut and can be dedicated to another vessel or cut.

Exit Time: The time between the end of the chambering operation and when the tow is clear of the lock.

First Come - First Served: A lock operating policy in which vessels are selected for service in the order in which they arrived at the lock, irrespective of travel direction; often abbreviated FCFS.

First In - First Out: A location on a waterway where tows are assembled and disassembled, or where the configuration of a tow is altered.

Fixed Weir Dam: Dam with fixed crest, where water level cannot be controlled.

Fleeting: Rearranging tows, usually to add or delete barges.

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Fleeting Area: A location on a waterway where tows are assembled and disassembled, or where the configuration of a tow is altered.

Fleet Mix: The composition of all vessels and barges used on a waterway.

Flow Regulation: Controlling of the flow of the waterway by river training or scheduled release of water from reservoirs.

Fly Approach: The type of approach executed when the lock has been idle and the inbound vessel proceeds directly to the chamber.

Fly Exit: The type of exit executed when the lock will be idle following the departure of the outbound vessel, that is, when no vessels are awaiting lockage.

Free Flowing River: A river unregulated by a system of locks and dams.

Hopper Dredge: Dredge which utilizes a draghead sliding over the bottom and forces material into hoppers of the vessel.

Hydraulic Cutterhead Dredge: A cutterhead dredge utilizing a centrifugal pump which moves a slurry of water and material from the bottom, transporting it to the point of discharge.

Hydrograph: Graphical relationship showing water level fluctuation elevations in time.

Hydrology: The science dealing with the properties, distributions and circulation of water.

INSA: Inland Navigations Systems Analysis.

Intracoastal Waterway: Inland route paralleling the coast for inland craft.

Jacknife Lockage: A type of lockage in which the tow is rearranged, usually from two barges wide to three, by breaking the face coupling on at least one barge and knockout of the towboat.

Jumbo Barge: A barge 195 feet long and 35 feet wide.

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Knockout Lockage: A type of lockage in which the towboat alone is separated from its barges and set alongside of them in the lock chamber.

Kort Nozzle: A funnel-shaped structure built around the propeller of a towboat to concentrate the flow of water to the propeller.

LASH: Lighter aboard ship; and international trade containerized cargo transportation system featuring shallow draft barges used for inland distribution which are carried in a ship over the oceans. LASH Barges are 70 feet long and 31 feet wide.

Lift: Refers to the difference in elevation between the upper and lower pools at a lock.

Light Boat: A towboat which is not pushing any barges.

Lock: A structure on a waterway equipped with gates so that the level of the water can be changed to raise or lower vessels from one level to another.

Lockage: Passage of a tow or other vessel through a lock. A normal lockage cycle consists of an approach, entry, chambering, and exit.

Lockage Time: The time elapsed from the start of approach of the first vessel or cut served by a lockage to the end of exit of the last vessel or cut served by a lockage. Includes the time required to disassemble and assemble multiple-cut tows and to rearrange setover tows, when such activities prevent the use of the lock by other vessels.

Morphology: Land form and structure.

Multiple-Cut Lockage: The type of lockage performed when a tow must be passed through the lock in two or more segments or "cuts."

Multiple-Vessel Lockage: A type of lockage in which more than one vessel or tow is served in a single lockage cycle.

Navigable Dam: A navigation dam which permits the passage of vessels without the use of a lock during periods of high water.

Navigable Pass: An operation whereby a vessel traverses a navigable dam without passing through a lock.

Navigation Season: That part of the year when the waterway is open to traffic.

Navigation Taper: Where floodwaters are released gradually in order to control the buildup of sediment.

N up/M down: A lock operating policy in which up to N upbound vessels are serviced, followed by up to M downbound vessels, where N and M are positive integers.

N up/N down: A commonly used special case of N-up/M-down, in which N and M are equal.

Non-Structural Measure: Proposed measure to improve navigation on a waterway or segment not involving building of a lock nor any structural modifications to the lock or waterway.

O & M: Operation and Maintenance.

One Way Reach: A reach narrow enough that two vessels may not pass simultaneously.

Open Pass: Passage of a vessel through a lock with no lock hardware operation. This is possible only when the upper and lower pool levels are nearly equal, and occurs most frequently at tidal locks.

Orange Peel Dredge: Similar to clamshell dredge.

Plain Suction Dredge: Utilizes suction alone to remove and transport dredge material.

PMS: Performance Monitoring System. The Corps of Engineers system for keeping and producing statistics at locks.

Pool: The body of water impounded by a dam.

Practical Capacity: As opposed to the hypothetical capacity of a lock, the actual maximum possible throughput under extant conditions.

Processing Time: The sum of all times taken to process a given tow through a specific lock (entry time, exit time, etc.).

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Recreational Lockage: A lockage of recreational craft.

Reach: A channel segment between two given points on a waterway.

Reliability: Refers to the percentage of time a facility is in use or able to be used.

Revetment: Material; either natural or artificial, used for bank protection.

River Stability: Measure of a river's ability to maintain its features over long periods of time.

River Mile: A number specifying the location of a point along a waterway, obtained as the distance from a reference point designated as mile zero.

River Training: Regulation of river flow utilizing dikes and revetments.

Scow: Large flat-bottomed vessel often pulled by a tug.

Seasonality: Fluctuations in conditions concurrent with the seasons of the year.

Seiches: Oscillations of the surface of a lake or land-locked sea that vary in a period from a few minutes to several hours.

Sensitivity Analysis: The analysis of multivariable functions holding one or more variables constant.

Service Time: The time taken to process a tow through a lock. Identical to processing time.

Setover Lockage: A lockage in which the towboat and one or more barges are separated as a unit from the remaining barges and set alongside of them in the lock chamber. The term is usually applied only to single lockages, but it could be used to describe any cut. The term is often used to refer to all types of single lockages requiring rearrangement of the tow.

Shoaling: Building up of sandbars through deposition of sediment.

Sidecasting Dredge: Utilizes a draghead sliding over the bottom, discharging dredged material over the side of the vessel back into the water.

Sill: A transverse structural element of a lock chamber upon which the lock gates rest when they are closed; the upstream or downstream boundary of a lock chamber.

Single Lockage: The type of lockage performed when the entire tow can fit into the lock chamber, with or without rearrangement, and hence requiring only one lock operating cycle.

Spillway: Overflow area of a dam.

Stage: Elevation of the water surface.

Standard Barge: A barge 175 feet long and 26 feet wide.

Straight Lockage: A lockage which does not require rearrangement of the tow in order for the tow to fit into the lock chamber. The term is usually applied only to single lockages, but it could be used to describe any cut.

Switchboat: A towboat used to assist tows requiring a multiple-cut lockage. A switchboat may be used to assist a tow in entering or exiting the lock chamber, or it may independently power a cut through the lock.

Tainter Valve: A valve consisting of a curved member rotating about a fixed point.

Technical Capacity: The maximum theoretical tonnage which can be put through a lock under specified circumstances.

Ton-Mile: A unit of transportation production equal to the movement of one ton a distance of one statute mile.

Tow: A towboat and one or more barges which are temporarily fastened together and operated as a single unit.

Towboat: A shallow-draft commercial vessel used to push or pull barges.

Tow Configuration: Orientation of barges tied together to form a tow.

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Training Works: Structures such as dikes or revetments placed along river channels to increase runoff capacity, prevent bank erosion, and stabilize the location of the channel.

Traffic Level: Volume of traffic.

Turnback: A lockage in which no vessels are served; a reversal of water level in a lock chamber with no vessels in the chamber. A turnback includes closing one set of gates, filling or emptying the chamber, and opening the other set of gates. Also called a "swingaround" or an "empty lockage."

Turnback Approach: The type of approach executed when the preceding event at the lock was a chamber turnback.

Turnback Exit: The type of exit executed when the next event is a lockage in the same direction, requiring a chamber turnback.

Watershed: A region or area bounded peripherally by water parting and draining to a particular body of water.

Waterway: Any body of water wide enough and deep enough to accommodate the passage of water craft, particularly commercial vessels.

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